A HISTORY
of
MECHANICAL INVENTIONS

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"Nunquam in aliqua ætate inventa fuit aliqua scientia, sed a principio mundi paulatim crevit sapientia, et adhuc non est completa in hac vita."

ROGERI BACON, Compendium Studii, cap. V.

Preface

This study of technology is an outcome of interests of many years standing. They found some outlet in the volume on the Industrial History of England, but many of the problems were not then clearly perceived, and there was no space for adequate presentation of the larger aspects of the problem. Subsequent experience in teaching has made it evident that the whole matter must be taken up systematically if the significance of technical innovation is to become an integral part of the historical analysis of economic phenomena. As the interests of the economic historian are merely those of the general reader, it is hoped that this study will be of interest to engineers and to the general public.

No attempt has been made to point out the full economic consequences of the technical progress recorded, and though the general chronology of the development has been given much attention the importance of the conclusions for the interpretation of the so-called "Industrial Revolution" is not developed in the present essay. The significance of the history of the inventions is obvious in many individual instances; the larger results, however, call for such extensive revisions of common judgments that adequate critical discussion of the problems raised would run to great length, and have little interest for many readers. It has seemed best to separate the history of the inventions from the discussion of their significance.

My obligations to the writings of Professor R. M. Ogden are acknowledged in the text, but I also owe much to personal discussion of these problems with him at an early stage in the preparation of the Manuscript. His suggestions were essential to the formulation of a concept of the process of innovation which is much more significant for historical work than any view suggested by the other groups of psychologists. From my colleagues Professors F. W. Taussig, A. H. Cole, and A. E. Monroe I have recieved important suggestions and encouragement. I am also deeply indebted to Mr. Walter B. Briggs for signal assistance at every stage of the work.

He has given me helpful guidance in the use of the resources of the library; he has done his utmost to insure the best utilization of its facilities; and he has secured the loan of many scarce volumes from other libraries.

ABBOTT PAYSON USHER.

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A HISTORY OF MECHANICAL INVENTIONS

Chapter I

THE PLACE OF TECHNOLOGY IN ECONOMIC HISTORY

I

Economic history is deeply concerned with the development of various associated subjects, but in particular with geography and the technological sciences. These disciplines deal with basic elements in economic history and without a just appreciation of the precise nature of their contributions no adequate interpretation of economic history is possible. The fact has long been recognized as a matter of abstract truth, but the materials of these allied subjects have been very imperfectly worked into the text of economic history. Economic history is the story of the mutual transformations taking place between human societies and their environment. Geography, broadly conceived, furnishes an account of the environmental factors that inevitably mould social life in many ways. The technological sciences furnish the account of the most important single factor in the active transformation of environment by human activity. Both of these sources must be utilized by the economic historian and the results effectively worked into the organized presentation of the historical record. The fact that these materials come from different sources is itself of assistance, for they indicate modes of arrangement that will do the least possible violence to the data of the record. These different factors must be separately analyzed and dealt with as specific elements because they are somewhat self-contained units in the story. We must deal with them separately because we feel them separately. But it must be evident that these two classes of material are equally important. Unfortunately, it has not yet

been possible to secure a well-balanced consideration of these fundamental elements.

Economic geography has made great progress during the last 50 years. The notable accomplishments of the vigorous French school were from the first significantly supplemented by the work of individuals in other countries, and latterly the recognition of the value of this direction of attention has made such headway that general position is thoroughly established in all countries. The essential principles are effectively formulated for instruction and methods of analysis are well established, though much remains to be done in applying these methods to the earlier historical periods. These results have been responsible for much extravagant geographical determinism; on the part of the specialists, no less than among the lay readers. Significant studies of the geographical data are frequently disfigured by naïve misconceptions of the relation of the phenomena to economic activity. The simplicity of the deterministic concept leads some economic historians to find the explanation of all economic changes in the simple facts about climate, minerals, or soil exhaustion. Class-room presentation of geographic factors is extremely difficult because of the likelihood of misinterpretation.

The natural antidote to these dangers is of course to be found in the materials of the technological sciences, and the development of these contacts is thus especially important to economic history at the present moment. Balanced judgment of the complex social phenomena of history will be easily achieved only when the different classes of material are presented with measurably equal effectiveness. We must have all the elements of the social process clearly presented to the mind; the geographical data bearing mainly upon passive adaptation to environment; the technological data, concerned with the process of active transformation of the environment through human agencies.

The adaptations with which economic geography deals are only in part historical phenomena. They are the spatial phenomena of social life; the analysis of the geographical data throws light chiefly upon the relations of different regions to each other at a given time, and upon the detail of settlement within particular regions. None of these matters can be ignored, but they obviously have to do with the description of conditions as of particular dates; and this is, of course, only one item in the historical record, just as the individual picture is an item of the series embodied in an

entire moving-picture film. The geographical data are a part of history, but in reality they are so small a part that they do not in themselves throw much light on the nature or character of the changes embodied in the total historical movement.

Geographical phenomena are, however, closely associated with one phase of social change; the growth of population and the consequent redistributions over the areas involved. Particular regions disclose progressive increases in density up to levels which can be explained largely in terms of differences in climate and resources. This growth seems to be somewhat independent of technical improvement, though the densities achievable are, at times, profoundly affected by technological advance.

These phenomena in their entirety involve the development of frontiers through the discovery of new habitable areas and ultimate redistributions of the massing of populations in the various areas by differential rates of growth or by actual migration. These phenomena are among the most complex of any presented to the historian. They involve all the factors operating in economic history and at present we are scarcely in position to attempt more than a preliminary analysis. It is clear that some of these changes are closely related to changes in the technique of transportation. It is very likely that the rapid extension of the effectively habitable area exerted some influence upon the development of technique in the first millenium of the Christian era. During that period, technological development seems to have been very slow; we are tempted to regard the predominance of frontier conditions as an explanation, because the economic pressure would be a less significant factor on the frontiers than in maturely settled regions. But it is possible to create presumptions in favor of the thesis that more technological development occurred in frontier regions than in the mature regions of dense settlement in the Near and Middle East. This situation might be explained on the grounds that the relative scarcity of labor on the frontier made it more necessary to utilize every possible mechanical device, and made it possible to utilize effectively devices that would have been too imperfect to be useful in a region in which skilled labor was relatively abundant and cheap.

It is obviously unwise to attempt to explain the "slow" rate of technical change in this or any other period until it is established that progress was "slow" in relation to some significant standard of judgment. In the present stage of our knowledge we are in

no position to make such a judgment; for there can be only one sound basis for comparison—the maximum achievement intellectually possible. This involves an extremely close judgment of the internal obstructions to invention in the total body of philosophic and scientific thought. There are grounds for believing that these obstructions were very great, but, obviously, it is not wise to attempt to deal with the more complex problems until the simpler and more objective problems have been tolerably well settled. Consequently, it is for the present wiser to confine attention to those matters that do not involve many interactions of the various factors. We need clear conceptions of the nature of the processes of invention and achievement. We need some measurable knowledge of the actual chronology of the development of the technique of industry and commerce, in its purely scientific aspects, as well as in its practical applications.

II

The purely geographic phenomena of history are essentially spatial, and for this reason they are not only deterministic in their bearings, but essentially unhistorical. The technological problems with which economic history is concerned present a sharp antithesis to these geographic factors. Changes in technique involve series of individual innovations that are finally embodied in practical accomplishments. These series or sequences of relatively independent inventions are among the most intense manifestations of the dynamic processes of history.

Each step in the sequence is a necessary part of the process; each step must needs be taken in the given order; consequently these processes of technological development are in form as well as in content the very essence of history. They are sequences of events which are intelligible only when read forward. They are sequences which can be interpreted adequately only after the events have occurred. They are thus deeply imbedded in time; they must be conceived as taking place in a kind of extension distinguishable from space which by nature admits of movement in any direction, indifferently. For some purposes of scientific thought, spatialized concepts of time are used without serious consequences, but in formal historical study it is essential to recognize that the record of history must be read forward. Historical process is a forward-moving development, incapable of prediction,

but yielding rational meaning when the full sequence of events is organized as an orderly progression from a demonstrable beginning to a significant end. Technical progress is historical process in this sense, and must be regarded as the essential and vital feature of economic history, for it is around these technical changes that all the phenomena of economic history must be grouped. There is a special value, too, in a separate study of the technological problems without regard for the moment to the detailed economic consequences of particular changes. The development of all these ultimate consequences would require a whole series of separate and measurably independent narratives, involving the activities of many different types of men and an amount of detail in which the larger elements of perspective over long periods of time would be irretrievably lost.

Economic history has been weakened in the past by the impersonality of its record. It has dealt so largely with classes, movements, and materialistic interpretations that the accomplishments of individuals have been lost. Few heroes have been put forward for popular admiration, and no little uncertainty has been shown as to the kinds of heroes to seek. The English empiricists were inclined to look to inventors and even the spiritually minded Carlyle said noble things of them. The German nationalists and the Socialists have given more attention to statesmen and political leaders, and this has been the prevailing view. This notion of economic statecraft as a socially creative activity finds itself in many logical and historical difficulties. The substantive benefits conferred by these "great men" are not easily pointed out and after a generation or two it is painfully obvious that the idols have feet of clay. The instincts of the empiricists were essentially trustworthy. The true heroes of economic history are the scientists, the inventors, and the explorers. To them is due the actual transformation of social life. Carlyle made only one error —he assumed that the movement of history could be attributed to the efforts of a very small number of uniquely gifted leaders. He failed to realize that the processes of history in their entirety involve not only the few who find themselves in strategically important positions, but also the many obscure and unrecognized innovators whose efforts were essential but not immediately significant or conspicuous. When it is recognized that the total achievement is the cumulative accomplishment of many men of considerable gradations in natural ability, the processes of history

become more comprehensible. Human accomplishment can then be presented as the result of continuous activity of common mental processes. It is no longer necessary to think in terms of intermittent manifestations of a mysterious transcendental power exhibited rarely and somewhat capriciously in men of genius. The process of innovation is relatively continuous.

Properly understood, the newer concepts of historical processes do not diminish the fame and honor of the great figures that have been esteemed in the past; but to their number many new names are added, some of equal talent, others of lesser talent, all worthy of honor.

The attribution of the function of innovation to the scientists, inventors, and explorers does not diminish the significance of the rôle of the statesman, but it conceives the character of his task in a different fashion. Instead of thinking of his work as creative innovation, it is presented in the light of a difficult task in the adaptation of the legal framework of society to changes in economic circumstance. This work becomes the last phase in the process of social change. First the technological changes, then the development of the consequences, finally the revision of law or custom. There is innovation involved in a measure, but these accomplishments are dominated to such a degree by current circumstance that their quality is more justly felt as an adaptation than as an innovation. The element of novelty has become diluted through many transformations and has acquired the status of a present fact. The statesman faces a "condition"; he is dominated by an external necessity. The inventor is dominated by his unfulfilled wish. Consequently, despite elements in common, the creative factors in the art of statecraft are subordinated to the adaptive. Of the important acts in history, the choices of the statesmen are the most elaborately conditioned by external circumstance.

The statesman, therefore, plays a part in economic history, but it is not the creative part attributed to him by the mercantilist, the nationalist, or the socialist. The actual rôle may seem to call for less originality of thought, and for a lower order of talent. In fact it is not less difficult, but different. The task is critical, rather than creative; it requires courage and social responsibility rather than brilliant, but possibly irresponsible, originality.

The presentation of economic history as being primarily a phase of the organized activity of the state thus laid the emphasis in the

wrong place. The policies of state are not the chief elements in economic development, nor are the statesmen the chief actors. George Unwin was perhaps carried rather far in his reaction against the political concepts of history embodied in the famous dictum of Seeley. "History is past polities; politics is present history." Unwin left the statesman a very subordinate rôle in any phase of history; quite possibly a smaller part in the total accomplishment than is just. But however that may be, the primary concept of Unwin is a notable contribution to historical thought. He finds the outcome of history in no particular form of church or state; whether Catholic or Protestant; absolute monarchy or republic; empire or national state. "The political outcome of today," he says, "cannot be justified as a creation. It bears a closer resemblance to that primeval anarchy before the light was divided from the darkness." The true outcome of history is to be found not in particular institutions, but in "the inward possessions and experiences of mankind—religion, art, literature, science, music, philosophy—but, above all, the ever widening and deepening communion of human minds and souls with each other." The chief creators of this result are to be found in the whole body of the people; in the reformers, the artists, the scientists, the scholars, the inventors.

Such a view carries us close to the deeper realities of history, and opens up new judgments of men and events which will make it easier for the historian to achieve the ultimate ideal of all historical writing—the presentation of a record in which we shall "see life without rearrangement."

Chapter II

THE PROCESS OF MECHANICAL INVENTION

I

The process of innovation has frequently been held to be an unusual and mysterious phenomenon of our mental life. It has been long regarded as the result of special processes of inspiration that are experienced only by persons of the special grade called men of genius. This mystical account of these phenomena is, however, gradually yielding ground before the growing body of psychological analysis, and we are beginning to realize that these phenomena of innovation are neither more nor less mysterious than the most humble and commonplace phases of our mental life. In the past we have underestimated the complexity of the processes of thought and behavior applied to the daily business of living, and we have failed to perceive the continuity of the gradation of mental activity from the most commonplace to the most distinguished accomplishments. The elements of difference do not consist in the development or application of essentially new types of mental activity; the processes that can be identified in the simpler and more immediate acts of living are applied to new and more remote objectives which can be achieved only by the finer perceptions and more fertile imagination of individuals that rise above the general level of the mass.

Innovation is an integral part of the process of learning, an inescapable necessity for the individual as for the group as a whole. It is doubtless true that our attention is commonly centered upon the conservative and imitative elements of the process of learning, so that we are likely to think of learning as a passive acceptance by the individual of a group tradition. But even in those societies where the weight of tradition is heaviest, there remain many daily problems that demand new judgments and responses on the part of the individual. No tradition is so complete as to be proof against the subtle transformations wrought by new precedents. The common law, which by theory is a comprehensive and pure

tradition, is not in practice a rigid and unchanging body of rules, but in fact the most fluid of all legal systems. It is based upon recorded precedent, but inasmuch as cases arise for which there is really no precedent, the process of innovation is ever a constructive force. It is so with all learning: there is a need of mastery of tradition, and there is also need of incessant innovation. False concepts of education and exaggerated respect for the canons of classical authority may obscure the actuality and significance of the learning of new things, but at the worst they do no more than obstruct and retard an inevitable process. The most skilfully contrived system of education can merely provide the most harmonious adjustment between these somewhat inconsistent and irreconcilable ends. It is truly difficult to impress upon the individual that necessity of facing both past and future symbolized in the image of Janus contemplating with equal attention both the eternity that is accomplished and the eternity that is to be.

Our powers of innovation are mysterious and in their entirety inexplicable; but so too are the other phases of the process of learning. The building of unorganized impulses and needs into a coherent personality of any grade or quality is no less mysterious in its processes than the most noted achievements of genius. Personality building is a persistent feature of all social life, and in some measure we must presume that all these processes reach back to the origins of human societies. In this respect, they are a commonplace phenomenon, but they are not for that reason the less mysterious. The discovery of similar mental processes at both extremes of mentality does not, therefore, withdraw the veil of mystery; rather is it spread impartially over the humblest commoner as over the greatest genius.

Throughout these gradations our mental processes fall into two types; the synthetic, constructive, and creative activities concerned with innovation; the analytical, imitative, and conservative activities concerned with the formulation and imposition of tradition. A comprehensive theory of innovation would involve by necessity all the synthetic activities, but it could not be confined to them because the analytical activities are called into play at several stages in the process. The data of experience must be organized and worked into consciously defined configurations or patterns. Some of these achievements in organization may obstruct particular innovations, but on the whole the enlargement of our significant experience is dependent upon systematic analysis

and organization. The unorganized content of the mind also plays an important part in innovation, and thus consideration of perception, memory, and imitation becomes an essential part of the study of innovation. Because the impulses to invention and discovery are deeply involved in the emotions, a comprehensive account must of necessity include the study of the emotional life from this special point of view. The innovating activities of the mind are thus synthetic not merely as regards the form in which their results are expressed. They are a synthesis of all the faculties of conscious life. Strictly speaking, any adequate theory of innovation would be an analysis of all the activities of the mind from a somewhat special point of view. The naïve error of common sense lies in the presumption that a specific and unusual process is responsible for accomplishments that express in a peculiarly intense degree the entire mental activity of admittedly unusual personalities. No single generalization or formula can summarize the process of innovation.

II

Mechanical invention, with which we are especially concerned, is only one phase of the innovating activities of the mind. A wide range of phenomena is included in the field as a whole, including the creative work of artists, scientists, and inventors. Although the work of exploration is a factor in the changing circumstances of economic life, it can hardly be considered a mental activity. When more than physical adventure is involved, it becomes a special phase of scientific or technological innovation. The true mental phenomena are highly complex both as regards the detail of the processes and as regards the objectives concerned, but at least two distinct types may be distinguished.

Discovery consists in the perception of relations existing in nature that were not previously recognized. Strictly speaking, the arrangements exist independently of our minds though obscured in many ways by the complexity of the phenomena. The perception of such relations turns largely upon eliminations and simplifications of the items of experience that may distract attention from the orderly patterns that are finally recognized. Many accomplishments of art and science are of this type. Scientific generalizations are the most obvious case, and we commonly speak of them as discoveries. In this case common sense requires no correction. The more realistic accomplishments in art are essentially similar. The landscape painter "discovers" a time of day and a point of view from which certain harmonies of mass and color can be

perceived. The more difficult task is the making of a record in which elimination of irrelevant detail and simplification of masses make the objects as seen by him evident to less-gifted perceptions. The sculptor discovers the beautiful pose. The musician discovers his themes. Elements of gradation are involved in these different phases of phenomena of discovery, ranging from the perception of relations that are always present down to relations which are only rarely present. In the lower ranges, the distinction between certain kinds of discovery and certain types of invention may not be very sharp. It is possible that careful analysis might establish the thesis that the process of invention is a development out of the process of discovery, and that in early stages of evolution we deal only with discoveries and not with inventions. But if this be the case, the distinction between the two types must have emerged at an early stage, for the apes of the laboratory at Teneriffe clearly seem to be capable of a limited range of inventive accomplishment.

Invention finds its distinctive feature in the constructive assimilation of preexisting elements into new syntheses, new patterns, or new configurations of behavior. The objectives may vary through a wide range: including at one extreme, creations intended to gratify æsthetic desires; and at the other, mechanical devices for the more facile gratification of material wants. Invention thus establishes relationships that did not previously exist. In its barest essence, the element of innovation lies in the completion of an incomplete pattern of behavior or in the improvement of a pattern that was unsatisfactory and inadequate. Innovation of this type appears in its lowest form in the learning of an act of skill which may not require any implements at all. Some significant innovation in behavior occurs when the directness of action characteristic of tne wholly naïve animal is qualified by the power to substitute roundabout methods whenever the direct method of gratification is obstructed.

The simplest demonstration of this type of behavior is provided by the detour problems that have been used in some experiments with animals and children. This type of problem should be carefully distinguished from the maze tests that are sometimes used. The detour test when properly staged makes it possible for the animal to see clearly all the elements of the problem, differing in this respect from the maze in which the general elements of the problem are not within the possible field of direct observation.

The test consists of bringing the animal within a three-sided enclosure and offering food outside the enclosure on the side directly opposite the opening. Care must obviously be exercised to avoid suggesting the opening to the subject of the experiment. Lower animals, such as hens, are practically powerless to solve such a test except by accident. Their behavior is largely restricted to motion in a direct line to the objective, and if that is obstructed they can modify their course of action only by luck. Young apes and dogs solve such tests with decision under most circumstances, but they may be puzzled and even made to fail completely if the food is placed so near the barrier that their attention becomes fixed upon the apparent accessibility of the object by the direct method of approach. The choice of the indirect, rather than the direct, means to the end involves in reality a substantial innovation in behavior; it presents in its simplest form the problem of surmounting obstacles to the gratification of wants which is the characteristic element in all invention. New patterns or modes of behavior must be established in such cases; and, if attention is given to the inner content of the case rather than to the external features,these new patterns are "invented" no less than the more complex patterns which include the use of instruments in the new solution. The addition of elements external to the animal merely makes the case somewhat more complex.

A modification of the detour problem tried with apes at Teneriffe is suggestive in this connection. Food is placed in a low three-sided enclosure in such a manner that the apes must first push it away from themselves with a stick in order to get it around the obstacle. Even after they had become thoroughly familiar with the use of a stick in procuring food, this test proved rather difficult and some could not solve the problem at all if the opening in the low enclosure were directly opposite. The angle at which they could solve the problem afforded apparently a measure of the relative intelligence of the different apes. Although, in such a test, the ape always had a clear view of all the elements of the problem, it was evidently more difficult for them than the detour problem in which they turned themselves completely around to avoid the obstacles. To adopt a somewhat indirect route to food was not a very difficult problem, but the necessity of pushing away something they really wanted encountered very serious resistances in their ordinary modes of behavior.

At the moment, the significant feature of the case lies in the fact that the increased resistance is not primarily due to the necessity of using an implement. The stick is merely an integral part in a pattern of behavior. Some new patterns involving a stick were quickly learned, but each new obstruction is a separate problem. There is thus ground for the opinion that the simplest form of invention is the establishment of new patterns of behavior; or more concretely, the acquisition of skill in meeting new situations.

Running and boxing, though they do not require any special instruments, are acts of skill no less than pole vaulting or rowing. The development of proficiency in any of these activities involves a transformation of behavior that is built up partly by the selection of new and effective modes of action that have been discovered, partly from inventions of new patterns. The instruments used are merely parts of an established system or pattern of events which cannot be divided.

Inventive activity extends through a wide range. In its more immediate forms it deals with the data of directly perceived experience. Both ends and means are explicitly present. In its more complex forms it appears in the field of the imagination, where its materials are the shifting complex of the images furnished by fancy or by the memory of actual experiences. Although the range is wide, throughout its full extent there is an actual identity in the processes involved. In all cases, the element of novelty consists in the assimilation of particular data into a pattern previously recognized as incomplete. The dominant fact is the gratification of obstructed wants. But in the more complex forms a distinction appears between the initial completion of the pattern in thought and the ultimate gratification of the want.

This element in the process appears clearly in the account we possess of the initial conception of the condensing chamber of the steam engine. In 1763, Watt was called upon to repair a model of Newcomen's engine belonging to the University. He had already been making a systematic study of some of the problems of heat and on that account made an attempt to determine the practical efficiency of the engine. After experiments he reached the conclusion that not less than three-fourths of the heat supplied by the engine was wasted by the alternate heating and cooling of the cylinder. The crucial idea did not come to him until 2 years after his first work on the engine and 6 years after his first

deliberate studies in the problems of heat. He describes the experience in these words:

"I had gone to take a walk on a fine Sabbath afternoon. I had entered the Green and passed the old washing house. I was thinking of the engine at the time. I had gone as far as the herd's house when the idea came into my mind that as steam was an elastic body it would rush into a vacuum, and if a connection were made between the cylinder and an exhausting vessel it would rush into it and might there be condensed without cooling the cylinder. I then saw that I must get rid of the condensed steam and injection water if I used a jet, as in Newcomen's engine. Two ways of doing this occurred to me: First, the water might be run off by a descending pipe, if an offlet could be got at the depth of 35 or 36 feet, and any air might be extracted by a small pump. The second was, to make the pump large enough to extract both water and air . . . I had not walked farther than the Golf-house, when the whole thing was arranged in my mind."[1]

The experience described is clearly the conclusion of the cycle of events which constitute the act of invention in the narrower sense. This imaginative perception of the final solution is the essential act of innovation. But such an experience is obviously different in its consequences from an experience at the level of bare perception. At that level the completion of the pattern results in the final gratification of the want. The ape Sultan gets his banana as soon as he solves his detour problem, or as soon as he perceives that a stick may be used to procure food lying outside the cage beyond the reach of his arm. When the incomplete pattern is filled out by an act of the imagination, the achievement consists in the perception of the means by which the want may ultimately be gratified. At the level of perception, therefore, the act of innovation is complete and final; at the level of the imagination, the essential act necessarily engenders further striving to attain the still relatively remote goal. Invention is at that stage no longer identical with achievement, if we think of achievement in its literal sense of an explicit gratification of a want. Much confusion of thought is due to the failure to distinguish sufficiently between the act of invention and the ultimate achievement based upon the imaginative act.

[1] THURSTON, "Steam Engine," p. 87.

III

It will now be desirable to give more attention to the details of the experiences involved in the process of invention. The experience is closely associated with the disposition of the mind to see things whole. We do not first perceive all the separate elements of an experience, and then subsequently combine them into an organized group. The whole mass of data is experienced as a unit, more or less satisfactory and complete. Such is the view of an important school of psychologists represented by Kurt Koffka, R. M. Ogden, and others. The thesis is clearly stated by Professor Ogden.

"A perception is any experienced circuit of events. In time it has a beginning and an end, although in the mesh of continuous happening, in which different strands are constantly overlapping, it is often difficult, if not impossible, to determine either an absolute beginning or a finite end; which leads us to wonder if time in its ever onflowing course, is really the safest guide in the analysis of experience. If it is not, then the conception of a circuit in which a want is satisfied is perhaps the truer description of adjustment. In turning full circle the end coincides with the beginning; in satisfying a want a gap is filled, and the want disappears."[2]

It is a great misfortune that there is no wholly adequate term to apply to this notion. In German the word *gestalt* is used; in English, *configuration:* but neither of these terms is sufficiently vivid or certain in its connotation. The school maintains that such perceptions possess inherently a unity that defies analysis. When we do succeed in breaking them up into their component parts, it is only by deliberate and, at times, protracted effort. Synthesis is more natural than analysis. The crude data of the imagination doubtless owe their structure to this essential unity of the things perceived. Such images present the inherent unity and the absence of separately perceived details which characterize the original experience. We perceive things as wholes.

The synthetic quality of experience, however, does not preclude wide gradations in the degree to which the various elements in a circuit make up a satisfactory and complete whole. Gratification is not always complete; the need or want may be wholly obstructed or satisfied incompletely. Innovation is thus in its primary features an attempt to complete or improve some configuration

[2] OGDEN, "Psychology and Education," p. 124.

felt by the mind to be unsatisfactory. There is thus an essentially æsthetic element involved in the selection of the most fitting or satisfactory method of completing particular circuits. Two wants are gratified: the desire explicitly felt; the desire to have a satisfying configuration.

The requirements of historical analysis of the development of mechanical appliances do not impose upon us the task of minute examination of the internal aspects of the mental processes. It will be sufficient for our purpose if we can secure a comprehensive description of the external features of the process by which the new configuration is reached.

We must think of the process as beginning with the recognition of a new or an incompletely gratified want. In most instances, we are concerned with improvements in the gratification of commonly recognized wants; but though the specific want is generally present, it does not necessarily follow that the inadequacy of current modes of gratification is always recognized. There are certainly many instances in which some of the distinctive contributions of the individual inventor lie in the perception of the inadequacy of current methods. This was true in part in the case of Watt's work with the steam engine: neither the nature nor the extent of the mechanical inefficiency of the Newcomen engine was generally known. In all probability there is some progressive change in the degree to which the need of an invention is obvious and commonly known. The problem, as such, is perhaps more obvious in later stages; but it is dangerous to follow such a theme very far. We may profitably consider the problem in a concrete case. Grinding was accomplished by mortars or saddle stones (see *infra*) until the third century B.C. when the rotary mill or quern was invented. How much direct gain in efficiency was there in such a change? How keenly or how generally were people dissatisfied with saddle stones and mortars? May we not presume that some special powers of perception were involved in the mere recognition that something better could perhaps be devised. The original inventor of the quern could hardly have foreseen the remoter consequences of the change: the possibility of applying animal power, water power, and ultimately wind power. We begin then with a consciously felt want; and though it may seem to be a commonplace beginning, it is not a point of departure that is certainly self-evident.

The second element in the establishment of a new configuration consists in the total experience of the individual inventor. The telephone and the phonograph are variants of a particular problem; the recreation of sound by mechanically controlled diaphragms. It is doubtless more than a matter of chance that we find Edison producing solutions of both phases of the problem. In part, this will reflect the general body of contemporary knowledge; but in nearly all cases the experience of the inventive individual is richer than usual along the lines of his special interests, and these differences are likely to play a decisive part in inventive accomplishments. Many illustrations can be found in the lives of George Stephenson, Bessemer, and Edison. Early work served significantly in furnishing their minds with interests and experiences which were turned to especially good account in the later and more commonly known inventions. These factors are largely responsible for vague elements of unity in the work of particular inventors —their work falls within certain limits, and reveals a style and quality which may be highly individualized.

These elements in the process of invention are fairly obvious. The next step may not at first seem necessary. Many may presume that the invention flows directly from the combination of a special problem with the highly individualized experience of the gifted inventor. The invention seems to be a mere putting together of the want and the experience. The biographies of inventors, however, show clearly that something else is involved. Popular opinion gives an entirely mystical explanation. Inspirations come to some men but not to others. Close attention to the detailed accounts of particular inventions affords a clue to the general character of the circumstances that promote the achievement of a new configuration. It is well-nigh indispensable that certain data of experience should be presented to the mind of the inventor in such a fashion as to suggest their connection with the problem. All the elements essential to the accomplishment must be brought together sufficiently to facilitate their organization into a new circuit or configuration.

In experimental work with the apes at Teneriffe, the results of the experiments were found to depend in no small measure upon the arrangement of the materials. In work concerning the use of sticks, everything depended upon the location of the stick with reference to the banana used as an object of desire. *The stage had to be set* with meticulous care, and conscious attention had to be

given every detail both in planning the experiment and in interpreting the results.

All inventive accomplishment involves some special setting of the stage. This phase of events is conspicuous in all "discoveries," and it is surely present in the work of invention. Edison's work with the incandescent lamp is somewhat of a border-line case between discovery and invention. Strictly speaking, the discovery of the properties of a carbon filament was a necessary condition of the invention of the lamp. The critical achievement was thus a discovery rather than an invention. He began experimenting with the problems of incandescence in 1878. Early work was based on platinum wire. The general fact of the lighting properties of incandescent wires had, of course, long been known, but all the experiments with metal wire had failed to give adequate results because the filaments were too short lived to be of any practical use. Some trials had been made with carbon rods. Edison's experiments with the incandescent light were contemporaneous with his work on the carbon transmitter for the telephone and the final achievement was actually based upon the casual presence on his laboratory table of lamp black that had been used in the telephone work. The story of the invention as told some months later in New York papers implies that the new association came to Edison as a result of his absent-mindedly rolling up between his thumb and forefinger some of the lamp black mixed with tar that was lying on the table. He had worked it into a kind of filament when the thought struck him that such a carbon element might solve the problem of his lamp. An experiment was finally tried with laboriously prepared apparatus and results were achieved which led to protracted experiment with various kinds of carbon filaments. These carbon products combined all the essential properties: resistance, infusibility and indestructibility. After prolonged experimentation with different kinds of vegetable fiber, filaments were turned out which ran to over 1,500 hours of life. From that stage the success of the general project was assured.

In this particular case, the carbon came as definitely into the line of vision between Edison and his projected lamp as the stick provided for the use of the ape Sultan came between the ape and his objective. It is difficult to secure wholly reliable illustrations of this special stage in the process of invention. Accounts are rather sketchy and many stories are based on memories and second-hand accounts. Furthermore, nearly all contemporaneous stories

are involved in the extreme complexities of modern accomplishments which present a substantial series of inventions rather than the specifically single act involved in the completion of a single configuration. Any account of this setting of the stage, therefore, must be accepted subject to some qualification, but there are certainly grounds for presuming that the circumstances of the staging of the scene are a crucial bridge between the past experience of the individual and the actual completion of the new configuration. Subsequent discussion of the nature of the obstructions to new configurations will afford further suggestions as to the importance of the circumstances involved in the setting of the stage.

Little remains to be said, beyond explicit and repeated emphasis upon the fact that the unity involved in the individual act of invention is brought to a close with the achievement of a single new concept, design, pattern, or configuration. The variety of words that may be used is indicative of the difficulty of adequately conveying the full connotation of the technical term "configuration."

IV

As soon as we recognize the necessity of restricting the act of invention to a single innovation, it becomes essential to distinguish a more general phase of the process of technological advance. The individual act of invention is not an isolated item, nor does any one invention make possible the full achievement of the potentialities implicit in the general concept or principle. It is thus important to recognize that these inventions form part of an orderly sequence, which embraces in its entirety the full record of the steps by which we achieve the complete realization of our ends. This interdependence of individual inventions upon each other appears even at the beginning of technical progress when all innovation is empirical, and restricted to the satisfaction of ends that are readily perceived and within the limits of immediate practical achievement. At this stage, each innovation has direct practical significance.

The development of flour milling affords an excellent illustration of the process of achievement under these conditions of pure empiricism. Early methods of grinding were based upon the laborious and inefficient action of saddle stones. These gave way to the mortar and pestle. The mortar was supplanted by the great quern, which in its early form was so heavy as to require the

efforts of two men or equivalent animal power. Only by slow stages was the mill developed into the pair of relatively flat stones, cut with grooves to accentuate the centrifugal forces upon which the action of the mill depended. Even the hand quern of the eleventh century represented, therefore, a long series of inventions accumulated during a period of twelve or fifteen hundred years. The number of inventions must be, of course, significantly enlarged if we consider the whole business of milling and include the development of various new methods of turning the mill. Even though many phases of such a process cannot now be explicitly dated, the general character of the development is not open to doubt. We may say, therefore, that even at the level of crude empiricism, the essential unity of the process of achievement is no less real than in the later period when there is more conscious perception of the ultimate ends towards which the inventors are working.

As the ends contemplated by the inventor become more remote and less and less capable of satisfaction by any single invention, the whole process of achievement becomes more explicitly conscious. The inventor realizes more or less clearly that the fulfilment of his purpose requires several related inventions and discoveries, and not merely a single innovation. He may recognize, perhaps, that he can do no more than work towards a goal which he is not likely to attain; though commonly he cherishes the hope that complete success lies just beyond his immediate reach. This change in the point of view of the inventor appears most explicitly in the case of Edison. When he proposed to create a complete domestic lighting system operated from a central power station, he consciously set himself a much larger task than the invention of an incandescent light, though the narrower project is frequently presented as his sole purpose. Nearly all the basic work in electricity was involved in the bare conception of such a project, and any description of the inventions which followed requires constant reference to all this early work. Edison thus proposed to himself an extensive synthesis of the electrical industry, with fairly clear consciousness of the magnitude of the task as of the possible consequences of such an achievement. It is hardly likely that this case could be duplicated in the earlier history of mechanical invention, for even when the process of achievement is largely directed by conscious recognition of the ultimate ends, we must realize that considerable phases of the general process precede clear recognition of the possible objectives, and that full consciousness of all the con-

sequences would not necessarily be present to the mind of any of the inventors engaged in the tasks of primary synthesis. The full unity of the process is thus likely to be appreciated only as an historical fact. Only as we look backward from the achieved results can we become wholly conscious of the full scope of the process by which the ends were attained.

This change in the character of the process of achievement involves ultimately the organization of research laboratories; and this increased deliberation of effort has given rise in the minds of many to an impression that the development of scientific knowledge makes some fundamental change in the character of the process of invention in the narrower sense. It is suggested that invention becomes more systematic and regular, and that the "inspirational" or saltatory elements are less considerable. It is, of course, an error to suppose that the essential quality of the individual innovation is in any way changed by the setting up of a laboratory; and a still greater error to suppose that there is anything new in the development of formal research looking toward technical innovation. The changes that have become conspicuous in the last 50 years are merely the completion of tendencies that have been significantly evident since the time of Leonardo da Vinci. They represent the accumulated result of two elements that were then more largely than ever before brought to bear upon technology: the first of these new factors was an organized body of scientific knowledge based deliberately upon experimentation; the second was a quickened imaginative perception of the consequences and potentialities implicit in simple abstract principles. It is the fruitfulness of scientific generalization that makes it possible to rise above narrow empiricism. Effective generalizations open up possibilities of abstract thought in which the immediate limitations of practical circumstances are partly overcome. They facilitate new correlations between means and ends, and taken in conjunction with fertile powers of imagination, they are likely to direct attention to ends that may be far beyond the limits of any immediate attainment. The discoveries of science define, or redefine, the problems of the inventor. The abstract methods of pure science furnish means for the elaboration of new technological concepts under conditions of extreme simplification. The process of achievement thus becomes conscious and deliberately directed towards its ends in proportion as the pure sciences

afford effective means of dealing with the realities involved in the specific problems of each case.

Early technological improvement is largely empirical, but the outstanding achievements have been accomplished only after scientific knowledge of principles opened up the way to full consciousness of the ends attainable and the means applicable to their satisfaction. The development of modern experimental science laid the foundations for our modern technology, and the primary changes in the character of the process of achievement appear in the sixteenth century as soon as the new scientific methods had redefined the problems of the mechanical sciences. Leonardo da Vinci, Gallileo, Huygens, Guericke, Papin combined research in pure science with interests in the possible applications of these new principles to mechanics. In so far as technical achievement becomes a conscious pursuit of relatively remote ends, it inevitably becomes a kind of research that is carried on by laboratory methods, even if the individual is working alone. The attainment of new results, however, requires the achievement of new configurations by processes that do not differ sensibly from the processes of innovation at lower levels of mental activity in the field of bare perception. In every case, the specific act of innovation completes a pattern or configuration that was previously felt to be incomplete. If the pattern is an abstract concept, the consequences may be different than thay would be in the case of a pattern involving concrete objects. The quality of the act, the resistances, and the mental processes would be essentially similar.

The application of organized science and the imaginative powers thus transforms the process of achievement much more than they transform the process of invention in its restricted sense. Under the guidance of conscious effort the process of technological improvement becomes more orderly; it proceeds towards a wider range of ends, and it undoubtedly achieves its ends more rapidly than would be possible under conditions of sheer empiricism. Empirical effort, however, is not entirely eliminated, because the body of scientific knowledge is never complete and at any given time may be utterly inadequate in particular fields. It is thus hardly too much to say that the development of science, more than any other single factor, transforms the process of empirical achievement into the process of conscious imaginative achievement.

V

An appreciation of the history of technical progress since the renaissance turns obviously upon an understanding of the nature of this imaginative process, and, if we may legitimately think of it as an orderly rational procedure, it should be possible to make some generalizations about its course. In dealing with the process of invention in the restricted sense, it was possible to find a basis for some generalizations in the conditions under which new configurations of behavior may be achieved. The process of achievement involves additional elements because it is more essential to find formulæ to express the relations of different acts of invention to each other than to stress the detail of any single item in the series. Three fairly distinct phases may be distinguished in the total process involved between the first discoveries of essential principles and the perfection of a group of machines capable of exhausting the possibilities implicit in the basic principle. We find, in the beginning, a series of discoveries and inventions which are relatively detached from each other. At an early stage, however, the work of synthesis begins: at first in the form of bare concepts expressed in verbal statements or perhaps embodied in sketches of some device or apparatus. Experiments may be made; some directed consciously towards a new concept, others concerned only with some specific scientific problem which proves ultimately to have consequences not at first noted. The net result of all this exploratory work is some fairly specific definition of a scheme or concept, so that the phase as a whole may be described as the elaboration of the concept.

With all this preliminary study of the basic elements in existence as a given body of knowledge, the stage is set for the primary synthesis. This work, if broadly conceived, will commonly embrace several inventions of commanding importance. They are, in fact, the strategic inventions which make the total achievement possible though they do not themselves exhaust the potentialities of the new devices. These inventions may exhibit considerable gradation in respect of the resistances overcome, and may present substantial variations in character. Some of them will involve highly novel syntheses, whereas others will exhibit extensive critical revisions of existing devices based upon scientific analysis and close reasoning from known principles. The characterization of this phase in terms of synthesis should not be allowed to obscure

the presence of this large amount of critical work embodied in some of the acts of invention and interspersed among them.

This feature of the work of synthesis tends to break down the sharpness of the distinction between this phase and the third and last phase of the process. One must recognize, however, that there is still a real difference between the task of converting a piece of laboratory apparatus into an adequate machine for practical use, and revisions of design and execution that accumulate in the course of a period as the result of the joint experience of the operators and the machine builders. The difference between the two phases of the process turns upon the relative importance of novel syntheses and critical revision. In the third and last phase, the critical elements are clearly predominant. The primary principles of the machines are not changed, but refinements of construction and design are introduced and features are introduced which were implicit though not at first perceived. The process of achievement as a whole thus consists of a combination of analysis and synthesis: critical analysis predominates in the early and late stages, while synthesis dominates the middle phase which we are prone to regard as the climax of creative effort. The process may be extended by further sytheses based upon one or more strategic inventions followed by critical work.

The purpose of these classifications will be clearer if we consider the concrete case of the history of the reciprocating engines. It should be evident that the general achievement must be defined in these broad terms. The history of the steam turbines involves a different set of principles, a different background in pure science, and an entirely different group of mechanical problems of design and construction. Hero's reaction turbine and Branca's impulse turbine are not really a part of the history of the group of reciprocating engines. On the other hand, it is clearly undesirable to relegate the development of the non-condensing engine to such a subordinate position as is frequently done in economic and historical literature. It is also essential to recognize the importance of the development of the double-acting condensing engine, in view of its relation to the establishment of the engine as a prime mover for general industrial use. The modifications required to perfect the locomotive and the steamboat are, of course, commonly recognized, though not always with much accuracy in respect of the elements of innovation contributed by the various inventors. Adequate regard for the requirements of unity demands, therefore,

that we should consider the whole group of machines based upon the general principle.

The first stage in the history of these machines begins with the discovery and formulation of the underlying principles of pressure in gasses. Cardan, Porta, and de Caus emancipated themselves from the confusion of the ancients in regard to steam and contributed some positive notions involving the use of steam as a pressure medium. The study of the vacuum pump and the redefinition of the problems of the vacuum were even more essential steps forward. The full achievement involved work by Galileo, Torricelli, Pascal, Boyle, and Guericke. The experiments of Guericke exhibited the use of pistons as a means of utilizing the pressure of the atmosphere, and thus afforded one of the most important leads toward mechanical application of the newly discovered forces.

In this preliminary stage, too, we must include much inventive effort. The general development of the vacuum pump was important. The plunger pump contributed the gland and stuffing box which were significant details for the arrangement of a piston in a cylinder. The inventions and experiments of Worcester, Savery, Papin, and Huygens led progressively towards an explicit concept of a steam engine, though no adequate synthesis was achieved. The work of the seventeenth century thus formulated the problem, and set the stage for Newcomen's synthesis.

Newcomen's invention of the atmospheric engine marks the beginning of the work of primary synthesis; and despite the limitations of the machine it must be regarded as one of the most brilliant and original concepts in the history of these engines. The notable critical work of Smeaton was concerned only with refinements of proportion, but Watt's studies led to a thorough revision of all the arrangements of the engine. Critical effort played the chief part in the early stages of his work, but the invention itself involved important new syntheses. In fact, no famous invention illustrates more completely the complexity of the act of invention at such a stage in the general process of achievement. No single incident could show more clearly the danger of treating an individual invention as an isolated event. Few great inventions are so obviously tied into their past, and it is rare that the critical effort required to bring them out is as protracted and as conspicuous as was the case with Watt's engine. The perfection of the design and the execution of the engine carried Watt and his associates to the limits of their powers. Some of the work involved

inventions of a secondary character that were in a sense implicit in the new circumstances. Some of the inventions of tool-making machinery were of first-class importance, and wholly independent. Much of the work involved merely sound critical application of known principles. Even if such work involves little specific invention, it is nonetheless an integral part of the total achievement. Such tasks can be accomplished most efficiently under what we call laboratory conditions; and the research laboratories of modern industrial concerns are largely occupied with such tasks of critical revision and elaboration. Important as this work is, it does not take the place of the primary syntheses embodied in the great inventions. It should be distinguished, too, from the experimental work carried on under more highly individualized conditions with reference to the actual work of invention and synthesis. Having regard to the different conditions of production, there is no ground for supposing that the tasks of critical revision were less adequately or less generally organized at the beginning of the nineteenth century than they are today. We must not regard the use of the laboratory as new either for critical revision or for fundamental experimentation and synthesis.

Despite large elements in common with Watt's engine, the non-condensing engines involved new problems of design and construction, so that one hesitates to rate as secondary the inventions of Trevithick and Evans. It may well be that the obstacles to the development of such concepts were sensibly diminished by Watt's effort, but they must nevertheless be considered as part of the primary synthesis along side of Watt's later patents on the double-acting and rotative engines. The decisive work of the Stephensons and Booth on the locomotive and of Fulton on the steamboat likewise deserves to be included in this work of primary synthesis. It was only through these combined efforts that the use of the new source of power could be extended to the full set of applications.

Thereafter, the work on the reciprocating engine was predominately a matter of critical elaboration. Better design and execution could increase the efficiency of the machine. New demands for large power units were met for many years by increasing the size of the engine. Inventions of significance, but of secondary character, were brought out; no commandingly novel syntheses appeared. This phase of development commonly has less interest to historians or economists except in so far as substantial changes

in performances are involved. As most of the changes were gradual the specific technical factors are seldom given much attention by persons outside the engineering profession.

VI

Much emphasis has been placed upon the pervasiveness of innovation and invention in our mental life in order to bring out the general content of the processes involved and in order to stress the extent and range of the interdependence of the activities of individual inventors. Some may feel that insufficient attention has been given to the truly great inventions, but, in recognizing the lesser and casual inventions that are a necessary part of all social progress, it is not necessary to depreciate in any way the quality of endeavor that is embodied in the work of the great heroes of this phase of human accomplishment. These epoch-making achievements are great, not because they involve a special process, but because of the unusual resistances to be overcome.

These accomplishments become spectacular because they involve some conspicuous break with tradition and thus reach out beyond the expectations which seemed to be justified by reason or recognized as legitimate by custom. In such cases, the individual seems to be set off against society and wages an important battle single handed.

These features of the greatest inventions and discoveries emphasize admirably a striking feature of the general process. We have already called attention to the fact that all innovation is in its essence the achievement of an obstructed wish. No attention has yet been given to the nature and extent of the obstruction. In some degree, of course, the obstacles are external, but, strictly speaking, the resistances are all internal. Only in so far as these obstructions are mental hazards can we hope to overcome them. Characteristically, the obstructions that count are the habits and dispositions previously acquired. Modes of behavior suitable for the attainment of certain ends may obstruct gratification if circumstances are changed. Thus, the detour problem in its simplest form gains its significance from the fact that animals first learn to move in direct lines towards their objectives. If the path is unobstructed, this is the best way of gratifying the want. If the path is obstructed, the disposition to move in a straight line towards the objective obstructs the necessary modification of

behavior, and with the lower animals proves to be an obstacle that is overcome only by chance. Past achievement—tradition—is not merely a means to certain ends, but a positive obstacle to their attainment under seemingly slight changes in conditions. At times, the behavior of a group of men is not much more intelligent than the performance of a flock of hens running helplessly up and down before a wire fence when a simple detour would solve their problem.

The obstruction, however, is a purely mental hazard. In its entirety our past must needs be the point of departure for all innovation. The difficulty is created by our attitude toward the past rather than by its own content. If we endow tradition with special sanctions of authority, and, still worse, if we set up the dogma that tradition is complete and final, then it becomes a hopeless obstacle to innovation. Unless the inadequacy of the existing configurations is felt keenly there is no incentive to innovation. Unfortunately, many of our social achievements are endowed with obstructive sanctions of authority. The concept of revealed truth, the concepts of canons of classical authority in science and in art are serious obstacles to innovation. The great achievements have been made by those who think in terms of a progressive revelation of truth, a progressive growth of science, a progressive development of art; the past then becomes the direct source of inspiration that it should be.

In the more immediate sense, our powers of innovation are obstructed by our personal habits. New syntheses are made difficult because we have become accustomed to ignore certain types of perceptions or images. In many respects, our conscious faculties are biassed in favor of conservatism. Our reasoning powers are primarily occupied with the organization of past experience. Our will is chiefly concerned with the maintenance of the honor of the personality that has already been created. The bias of reason is perhaps the more important in connection with the problems of invention. After all, it is a wholly natural circumstance; for reason works mainly by analysis towards critical ends. The synthetic activities of our minds concerned with innovation are antithetical in many ways. They are more closely associated with the emotions than with reason in its narrower meaning, and it is perhaps correct to say that they are æsthetic and intuitive in character rather than rational. The wholly skilful act "feels" right; the image that completes the configuration is fitted into place because

it meets the æsthetic and emotional requirements of the case. Later, it may be possible to work out the rational grounds of the matter, but there are many cases in which the rational grounds were so incompletely perceived that they could have exerted little effective part in the accomplishment.

On the whole, the crucial features of acts of innovation take place in the emotional field rather than in the field of critical reason, and by necessity of circumstance the special features of obstructed desires are deeply involved in all innovation. In many instances the processes of innovation are accompanied by genuinely pathological features, though as might be supposed such extremes are most common with "inventors" who fail entirely or almost entirely. Abnormal phenomena are in fairly direct proportion to the degree of obstruction. With men like Edison and Bessemer, whose careers are records of continuous achievement, life is intense but convincingly normal.

In all cases, however, the emotional quality of the phenomena appears in the manner in which the subconscious activities of the mind are involved. Once invention is established in the field of the imagination, these subconscious faculties become an inevitable factor in the process. The wishes that we find it difficult to gratify by our deliberate, conscious activities take up their abode in the domain of the subconscious mind: for better or for worse. The inventor, like the artist, lives on the border land between the normal and the abnormal, and like artists and prophets finds in his day dreams a source of gratification and encouragement at the least, and at times a fruitful source of genuine accomplishment. Intuitive knowledge and the works of creative imagination are more or less directly associated with delvings into levels beyond the limits of our normally conscious life.

The domain of the subconscious mental life must be divided into at least two fields; in general, the activities of the mind during sleep can be distinguished from the involuntary activities of the mind during wakeful hours. The boundaries are obscure, most especially as regards the transitions between deliberately directed reflection and uncontrolled reveries, but these various levels of mental activity are clearly present. Varendonck, working upon the basis of the Freudian psychology, reaches the conclusion that the thought processes at all three levels are essentially similar in their general elements though they vary widely in degree. It is fairly evident, too, that the uncontrolled reverie or day dream is

not without positive value in the mental life of the individual, and under certain conditions it may cooperate with deliberate reflection to produce distinctive achievements in innovation.

The thinking that takes place in day dreaming seems chaotic and disorderly because it lacks the logical discipline that dominates our directed reflection even when little formal training is involved. This feature, however, is an inevitable consequence of the purposes that dominate this distinctive group of mental processes. It is the emotions rather than the critical faculties of the mind that are to be served; the direct gratification of emotional needs is the essential object of these activities. Thus, distinctions between the real and the unreal, the possible and the impossible count for little in the realm of day dreams. The wish is father to the thought, and we find ourselves projected into scenes which represent the fulfilments of our desires. In so far as these mental activities are purposeful they are concerned with the unsolved problems of our future, without discrimination between the trivial and the important. By their very nature, such processes are intimately associated with precisely the kind of task that emerges in all innovation. The purely emotional needs involved in the incomplete configuration tend in themselves to engage this fore-conscious attention, and lead towards gratification of the obstructed wish merely because it is obstructed. By reason of the primary characteristic of these uncontrolled reflections, the obstacles to accomplishment are sensibly diminished. The probability of achievement is further increased by the wider range of the memory system that is open to the mind at the level of day dreaming. Our deliberately conscious reflection reduces its materials to order by a ruthless elimination of large masses of the crude data of perception and memory. This is an element of strength when the purposes of our mental activity are well defined and when the means to such ends are clearly perceived. If the particular problem cannot be solved readily by methods of deliberate reflection, the sacrifice of a large portion of the memory system may become a serious element of weakness. If conscious reflection sets up additional hazards by stigmatizing the wish as "unreasonable" or "impossible," then fulfilment by the methods of conscious thinking is practically out of the question.

Under such conditions, the tendencies of thought at the level of fore-consciousness afford the only possibility of reaching a solution of the problem. The disregard of "logic" and "reality" promptly

removes all the inhibitions of the overdisciplined voluntary mind. The utilization of the entire field of memory furnishes a richer array of materials than is afforded at the level of full consciousness. The emotional demands of the entire personality engender trains of thought or images from which a solution may be selected.

The two types of thinking, the voluntary and the uncontrolled reverie, are thus essentially complementary. Emotional color is lost and for purposes of innovation weaknesses appear in the processes of controlled reflection. These elements are recovered in the more primitive processes of thinking that take place at what we are prone to call the "lower" level of the fore-consciousness. But evidently these discriminations of higher and lower involve distinctions that are not wholly borne out by the full record of mental achievement. Our greatest constructive accomplishments seem to be initiated largely if not exclusively by this so-called "lower" kind of thinking; and not by accident or hazard but by the nature of the case. Our so-called "higher" faculties are cold and conservative; without the purpose or the power for great achievement. At the same time, these methods furnish an indispensible critical control. Both types of thinking must be used. Invention thus involves the whole activity of the mind, and as yet we are inadequately aware of the complexity and comprehensiveness of the "whole."

Chapter III

THE EARLY HISTORY OF THE PURE AND APPLIED MECHANICAL SCIENCES

I

Science arises out of practical experience. It is an attempt to communicate acquired experience with the maximum economy of statement. Science, therefore, appears only after considerable accumulations of experience, and for a long period it is merely a commentary upon the general practice of the arts and crafts involved. Not until substantial achievements in analysis have occurred does science begin to exert a creative influence upon the processes of discovery and invention. Carefully considered, the early treatises upon the mechanical sciences are an important part of the historical evidence bearing upon the technical proficiency of the early period, but such material must be used with caution because for many centuries, practice was in advance of theory. The balance was in use in Egypt more than one thousand years prior to the earliest formal treatise on the theory of the balance, and antiquity did not achieve a fully adequate theory of the equilibrium of the balance in all positions. In its early history, science is thus a factor in the diffusion of knowledge rather than a direct means to new practical achievement. In the light of modern knowledge early scientific achievements seem naïve and slight. Their relation to contemporary practice differs so largely from what we might expect that there is serious danger of failure to appreciate the nature and extent of the early achievements.

From the historical point of view their interest lies in the light thrown upon the nature of the factors that limit accomplishment, and with a little scrutiny it will be seen that the difficulties are largely internal. Early achievements obstruct further growth. It is important to recognize, however, that the practical needs are themselves limited in scope.

The objects of science lead naturally to generalization and simplification. The phenomena as perceived are analyzed into simple

components and these in turn are referred to one or more principles. In so far as these accomplishments are largely empirical no particular problems arise. Both general and simplified data are closely related to experience and though results may not be large, they are not likely to be vitiated by positive errors. The attempts at generalization, however, lead to the recognition of connections among the various sciences and between the sciences as a group and the broader problems of philosophy. It is at this stage that complications arise in Greek achievements in the mechanical sciences. Interest in the problems of mechanics developed from several directions. The problems of equilibrium or statics were implicit in the five "simple" machines, some of which had long been in use, while others were coming into active use contemporaneously with the development of science. The problems of dynamics, however, arose most conspicuously in connection with astronomy. Furthermore, the extension of analysis to the mechanical fields was in part an outcome of the endeavor of the Peripatetic school to formulate a comprehensive body of philosophic and scientific truth. The particular sciences took form, therefore, when there was active discussion of the purely general problems of the relation of the sciences to each other. The status of the sciences in relation to each other and the methods appropriate to scientific inquiry were inevitably influenced by the general discussion of the nature of truth.

Both Platonists and Aristotelians inclined strongly towards a concept of truth as absolute and eternal: isolated passages occur which might be interpreted as a recognition of a doctrine of relativity. Other schools held doctrines which challenged the concept of absolute truth. But the primary object of philosophy came to be defined as the discovery of the eternal truths of nature and the task of the sciences was appropriately defined as the construction of hypotheses which would present the phenomena of nature as manifestations of the eternal truths.

This general concept of the task of science was in the mechanical sciences largely responsible for the subordination of experimentation to logical demonstration after mathematical principles. It is for this reason, that the statement is frequently made that experimental methods were not used by the Greeks. The error of this statement is now widely recognized, though the mistake is still frequently encountered. Experiments were made, but with objectives that were more limited than in modern science. With the

early scientists, experimentation was incidental and casual, not until the close of the Middle Ages were the mechanical sciences definitely placed upon a foundation of verifiable experience derived from systematic and progressive experimentation. Until then the mechanical sciences of a formal character rested upon supposedly self-evident axioms, or upon primary metaphysical concepts. Attention was thus directed toward logical demonstrations and toward mathematical theorems that involved pure reasoning rather than towards experimental study of the phenomena. Formal mechanics was thus restricted in antiquity to the demonstration of the principle of the lever and to the manifestations of that principle in the five simple machines. For these purposes it was not necessary to revise or simplify the phenomena of general experience. In a strict sense, the classic demonstrations are accompanied by carefully devised experiments though we are not likely to think of them as such because they do not lead to any revision of the findings of common sense. The emphasis is placed upon intuitive perception and the symmetry of the arrangement so that it becomes a demonstration of *why* the phenomena assume the form they do. It is not an experimental analysis of *how* the phenomena take place.

In addition to the formal treatises on the principles of mechanics, thus restricted to the field of statics, there was much consideration of the problems of dynamics incidental to astronomy and general philosophy. But these problems were not effectively solved, positive errors of varying magnitude appear in nearly all instances. Elements of bias obscured important factors in all these phenomena, and it proved to be exceedingly difficult to overcome these errors.

A third group of treatises must also be recognized, comprising works of an essentially empirical character; general descriptions of the applications of the five simple machines and their combinations; descriptions of particular machines, such as the water clock, the organ and the various mechanical devices used in temples; the treatises on pneumatics, concerned with the analysis and application of a varied group of phenomena involving atmospheric pressure, pressure in liquids, and pressures developed by the expansion of air, by steam, and the like.

The treatises on pneumatics are especially significant because they reveal positive applications of experimental methods: the significance of this development in method was limited; partly because the immediate accomplishments were modest, partly

because it did not lead to the recognition of the need of any protracted or systematic effort to correct the data of general experience. The answers achieved satisfied immediate practical needs so that investigation of the phenomena came to an end at that point.

II

Historical as well as theoretical requirements make it desirable to distinguish at least two schools of Greek writers upon the mechanical sciences; the Aristotelian school, and the school of Archimedes. There were important differences in method between the two groups. Furthermore, the works of Archimedes were not known in Latin Europe until the Greek renaissance so that they exerted no direct influence on medieval science in its formative period. The Aristotelian writings, thus, possess a greater historical importance than many modern writers on mechanics are inclined to ascribe to them, and recent researches in the history of these sciences consider them intrinsically more significant for the development of modern thought and method.

The work of the Aristotelian school is scattered through a large portion of the general Aristotelian corpus. The concepts of dynamics appear only as features of the general theory of physics, and thus involve large portions of the primary treatises: the eight books on physics, the four books on the heavens, the two books of the treatise on generation and destruction, the four books on meteors, the thirteen books on metaphysics. The concepts of dynamics are clearly an integral part of the general philosophy of the school, and it was partly for that reason that difficulties encountered in particular phases of mechanics were not readily solved. Because they were of subordinate importance, they did not exert a subversive influence when they seemed to be insoluble or even when they were solved in a manner that was measurably inconsistent with the general theory.

The general principles of dynamics are summarized in the treatise known in the middle ages as "The Treatise of Euclid on Weights" (*Liber Euclidis de ponderibus secundum terminarum circumferentiam*). The attribution to Euclid is certainly erroneous, but the treatise was printed in early editions of Euclid. The Peripatetic theory of statics first appeared in the small treatise "Mechanical Problems," which bears Aristotle's name throughout the Middle Ages though now held to be the work of some member of the school more or less contemporaneous with Aristotle. Fol-

lowing this in logical order is the "Book of Euclid on the Balance," which represents a transition between the early Aristotelian method and the method of Archimedes. Of somewhat similar scope, but wholly uncertain in date is the little treatise known to the Arabs as the "Liber Charastonis." This is also a theory of the balance following in general the method of the treatise "Mechanical Problems." The date of the treatise is wholly uncertain. It may be contemporary with the treatises ascribed to Euclid and thus prior to Archimedes, or it may be the work of one of the Alexandrine writers of the time of Claudius Ptolemy. If this is the case, it bears specific testimony to the vitality of the Aristotelian method and its ultimate dominance in the field of the mechanical sciences. Fortunately, the importance of Aristotle does not rest upon such an insecure foundation as the date of a single treatise. The treatise of Hero of Alexandria on "Mechanics" affords decisive evidence of the primary importance of the general method of the Peripatetic school despite some indebtedness to Archimedes. The dates of Hero are wholly uncertain but it seems now that the earliest possible date is the latter half of the first century B.C., and the latest possible date is the second century A.D. In any event, his work must be associated with the final revision of Aristotelain science that culminated in the astronomical work of Claudius Ptolemy. The treatises of Hero embody the matured achievement of the Peripatetic school in the field of mechanics. It is a curious, but possibly not an important fact, that the primary treatise of Hero was not known in its entirety to the Christian writers of medieval or early modern Europe. The only complete texts are based on Arabic versions which were scarcely known in Europe until the close of the nineteenth century. The Aristotelian tradition was thus known to Latin Europe in a somewhat incomplete and inferior literary form, but all essential features of the body of doctrine were in the hands of European scholars from the time of the Latin renaissance.

The essential features of the Aristotelian treatment of statics are embodied in the following passage:

"The phenomena observed in the balance can be referred to the circle, and those observed in the lever to the balance; while practically all the other phenomena of mechanical motion are connected with the lever. Furthermore, since no two points on one and the same radius travel with the same rapidity, but of the two points that which is further from the fixed center travels more quickly,

many marvellous phenomena occur in the motions of circles, which will be demonstrated in the following problems."[3]

Duhem considers this concept the foundation of the mechanical sciences. Though it shows little concern with the demonstration of the truth of the propositions about the balance, it represents a higher order of synthesis than the later achievement of Archimedes (as embodied in the extant treatise on the equilibrium of planes). Its implications and suggestions are far reaching. Fully elaborated, this Aristotelain proposition becomes a comprehensive generalization for the lever in all positions. The work of complete demonstration would necessarily involve the concept of the

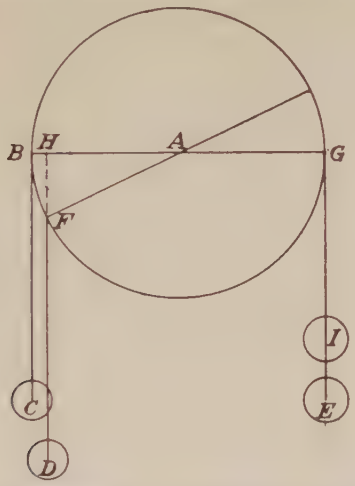

FIG. 1.—Hero's demonstration of unequal weights in equilibrium.

moments of a force, as well as suggest essentially modern methods of analysis based on the concepts of infinitesimals.

Practically considered, this approach emphasized the various aspects of mechanical advantage in the proportions between the intensities of forces and the distances through which they operate. It thus afforded a more helpful mode of explaining the problems of the five simple machines than the rigorous geometrical method of the extant works of Archimedes.

The Aristotelain influence appears clearly in the last proposition of the first book of Hero's "Mechanics" (Book I (34).

"Suppose we have a wheel or mobile pulley set upon an axle whose center is *A*: the diameter of the wheel will be the line parallel

[3] ARISTOTLE, "Mechanica," p. 848*a*.

to the horizon. At the points B and G two cords are attached, to which are suspended equal weights. It is evident that the pulley will not move in either direction, because the weights are equal and the distances from the center are equal. Suppose, however, that the weight C is heavier than the weight E; it is evident that the pulley will be drawn down on that side, and the point B will descend with its weight. We must discover at what position the heavier weight will come to rest after its descent. Let us then lower the point B and bring it to F; the cord BC will come to the position FD and the weight will stop. It is clear that the cord GE will be rolled up in the throat of the pulley and that the weight will still be suspended at the point G. The line DF, if prolonged, comes to H. Since the two weights are in equilibrium, the ratio of their weights is the inverse of the ratio of the distances of the points of suspension from A. Thus $\frac{HA}{AG}$ is equal to the ratio of the weight E to the weight D. We may apply the same reasoning to any other weight. It is thus possible to balance any given weight with a smaller weight."[4]

This proposition and the two propositions which precede it in Hero's treatise imply the concept of the statical moment: that is, the notion that the "length" of the arm of an irregularly shaped or bent lever must be interpreted as the perpendicular distance from the line of action of the force to the point of support. This concept is, of course, fundamental to any generalized interpretation of the problems of the lever, but though stated for particular cases the principle was not clearly apprehended in antiquity. As one of Hero's propositions is said to be taken from Archimedes (presumably from the last treatise), the concept emerged at an early date in the history of mechanical science, but it was not clearly apprehended until the close of the Middle Ages. It was a strategically important concept, for no substantial development of statics could take place until this notion was fully apprehended in its generalized form.

The difficulties encountered in the formulation of the principles of dynamics were greater than in the field of statics, for here the intrusion of general metaphysical notions was considerable and

[4] Schmidt, "*Heronis opera*," Vol. II, 1, pp. 88–91; Carra de Vaux, "*Les mécaniques ou l'élévateur de Heron d'Alexandrie; Journal Asiatique*, 9e Série. II. pp. 190–192, 1893. As the figure in the Arabic text is incorrect, the figure reproduced has been altered to conform to the text.

the need of experimental analysis of the perceptions of common sense peculiarly acute. The terminology itself diverges at many points from modern usage. The concept of motion or movement is applied to change in a very broad sense. This general classification comprises four different types: change of substance, including generation and decay; quantitative change, increase or decrease in volume; qualitative change, involving transformation of the properties of bodies; change of place, or motion in the modern sense of the word. This grouping of the phenomena of motion with the general problems of change is particularly significant in any consideration of the resistances opposed to the development of science. Problems of dynamics fared little better than the intrinsically more difficult problems of development and evolution. The classification is more than a mere matter of variations in the use of words.

Changes of place were divided into several categories. Two kinds of "simple" motion were recognized; circular motion or rotation, and rectilinear motion. The former pertained to celestial bodies, and was held to share with them the perfection of their nature. The notion is developed at some length in the commentary of Simplicius.

"The heavens move with the movement of rotation, but neither up or down: rotation is in fact the motion of a body which taken in its entirety does not pass from one place to another, although its parts are actuated by a local movement. A body which rotates upon its own axis may have a certain kind of position; as its parts are in contact with each other, they establish spatial relations to each other; but such space is particular to the parts. There is no space with reference to the Universe as a whole, because there is no body outside the universe that is contiguous with it. It cannot move up or down for then it would change its general position; but it can turn upon its axis."[5]

It is not a part of the problem of the mechanical sciences to consider the transition from motions of the concentric spheres as originally conceived to the motions of individual heavenly bodies as provided ultimately with circular orbits figured as cycles and epicycles. It is, however, a matter of deep moment to recognize that the concepts of rotational movement and of circular orbits seemed "simple" and "natural" to the Greek philosophers. These propositions were held to be truths to which the hypotheses

[5] Cited by DUHEM, "*Système du monde*," Vol. I, p. 203.

of science must needs conform. The task of astronomy was to find appropriate means of harmonizing observed phenomena with these concepts. As originally stated, the problem was incapable of any solution, and in a strict sense the hypotheses of Ptolemy involved some changes in the concepts of the motions of the heavenly bodies, but the modifications did less violence to the general metaphysical concepts than would have been involved in a theory of elliptical planetary orbits with appropriate distinctions between the solar system and the fixed stars. The heliocentric hypothesis appeared in the works of some of the Greek scientists, but it was not worked out in sufficient detail to make it possible to compute positions of the planets and stars. Ptolemy's hypotheses made such computations possible with a minimum of metaphysical heresy.

Terrestrial objects were deemed to display natural motions in straight lines. Heavy bodies by nature fell towards the center of the earth. Light bodies, naturally rose to the air. But at the terrestrial level "violent" motion also appeared, either as a circular motion or as rectilinear motion or as a combination of the two. The flight of a projectile was thus figured to the Greek mind as composed of movement in straight lines combined with movement in the arc of a circle. To these propositions was added a serious error of observation. It was held that heavy bodies fell more rapidly than light bodies, not only under special conditions involving differences in form and therefore in resistance, but under all conditions. The basic concepts of Peripatetic dynamics were therefore a source of many serious difficulties when applied to concrete phenomena.

Violent motion was conceived as being produced by the continuous application of a force.

"How is it that a body is carried along by a motion not its own, if that which started it does not keep following and pushing it along? Is it not clear that in the beginning the impelling force so acted as to push one thing along, and this in turn pushes along something else?"[6]

In the case of projectiles it was presumed that the movement of the air behind the projectile maintained the continuity of motion. There are other passages in which the resistance of the medium in which a body is moving is recognized, but that notion was not systematically applied because no satisfactory abstraction could

[6] ARISTOTLE, "Mechanica," p. 858*a*.

be made distinguishing between movement in a given medium and movement in a vacuum.

The problem of the vacuum was of the utmost significance in the development of mechanics. For the Peripatetic school a vacuum was inconceivable because it was inconsistent with a theorem concerning the proportionality between the force exerted, the resistance encountered, and the speed attained. The generalization was derived from direct perception of the commonplace phenomena of traction. The movement of a wagon over the ground requires a force equal to the speed attained multiplied by the resistance encountered. The beaching of a vessel by a group of men displays the phenomena with considerable variety of detail. Hence the formulation of the principle: $F = RV$. Applied to the problem of motion in a vacuum this principle leads to the inference that if there were no resistance the change of place would be accomplished instantaneously. The Peripatetics, concluded therefore, that the atomists were in error when they conceived the vacuum to be the cause of all motion. The generalization of Aristotle was accepted because it seemed to fit the facts.

"The rejection of the dynamics of Aristotle and the establishment of modern concepts involved the appreciation of the complexity of the commonplace experiences of daily life. The motion of a vessel drawn by boatmen, the motion of a wagon on its wheels are not simple, elementary facts to be explained directly by the principles of science. They must be regarded, on the contrary, as motions of extreme complexity, a rôle of great importance is played by the various resistances, which must be eliminated before genuinely simple phenomena can be conceived. In short, to formulate the principles of the science of motion, it is necessary to make the abstraction implicit in the consideration of single force acting in a vacuum. Such a force was inconceivable to Aristotle."[7]

The problems of the vacuum appeared, however, in connection with the study of siphons and pneumatic apparatus and it is significant to note the modest extent of the corrections suggested by the scientists. The use of the siphon extends far back into Egyptian history. It appears in the reliefs as early as the eighteenth dynasty (1500 B.C.) as a means of decanting liquids from the large earthenware jars used for the storage of oil. Systematic treatises on pneumatics begin with Ctesibius, and the work of his pupil Philo of Byzantium has come down to us through an Arabic

[7] DUHEM, "*Système du monde*," Vol. I, p. 195.

translation. The treatise begins with the description of a number of simple experiments designed to demonstrate two propositions; that air is a body which fills all vessels not containing liquids or other substances; that the removal of the air in siphons or other specially constructed vessels results in the prompt replacement of the air by the liquid in the vessel. Philo does not associate these experiments very specifically with the general problem of the vacuum, but Strato (*c.* 288 B.C.) analyzed these problems and Hero of Alexandria finally incorporated Strato's work in the general body of doctrine of pneumatics. The study of Strato confirmed the position of the atomists in all essential particulars and led to the conclusion that an artificial vacuum could be created.

"Upon the basis of these experiments we may take the position that every body consists of small molecules, between which still smaller vacua exist. We may say in general that there can be no continuous vacuum, and that unless some external force is exerted everything is filled with air or water or some such substance. In such measure as one of these elements is displaced some other element immediately flows in and occupies the vacuum. It may be maintained, further, that a continuous vacuum is impossible unless some force external to nature is exerted, and similarly that a vacuum can at times be created by artificial means."[8]

This is perhaps one of the most striking single indices of the vitality of the work of the late Alexandrine school. It shows significant independence from tradition, active and effective syntheses of positions earlier held to be mutually contradictory, deliberate experimentation as a basis of scientific analysis. But this treatment of the problem of the vacuum was of limited significance, because the consequences were not worked out in the general field of dynamics.

In the field of statics, the treatise of Archimedes on the "Equilibrium of Planes" presents a striking contrast to the Aristotelian work. The reference to the properties of the circle in the Peripatetic school minimized the separation of the two branches of mechanics. The application of geometrical methods, by Archimedes set up a rigid distinction and resulted in a narrow conception of the problems and methods appropriate to the analysis of the problems of statics. Five postulates are laid down as self-evident truths. A series of important propositions is then established by rigorous reasoning upon the basis of the postulates.

[8] SCHMIDT, "*Heronis opera*," Vol. I., p. 29; 5–31.

There are references to a treatise on the lever, which is now lost. If we may judge by the references given in later writers this treatise was based on the methods of the Peripatetic school. Duhem holds that the treatise was incorrectly ascribed to Archimedes, and that it should be identified with the treatise on the balance that was called by the Arabs the "Book of Chariston," or in Latin "*Liber Charistonis*."[9] None of the characteristic work of Archimedes was known to the scholars of Latin Europe until the close of the fifteenth century. The methods of Archimedes exerted a profound influence upon the presentation of the results of modern work. Continuity of reasoning was preserved, as an ideal, but the basis of scientific analysis was furnished by the verifiable data of experience as established by experimentation.

Modern writers hold that the work of Archimedes in the mechanical sciences was dominated by a mistaken notion of the nature of the proofs that are possible or necessary. Consciously or unconsciously, Archimedes attributed a superior quality to instinctive knowledge. The status of the intuitive and reflective processes is well described by Mach.

"Instinctive knowledge enjoys our exceptional confidence. No longer knowing how we acquired it, we cannot criticize the logic by which it was inferred. We have personally contributed nothing to its production. It confronts us with a force and irresistibleness foreign to the products of voluntary reflective experience. It appears to us as something free from subjectivity, and extraneous to us, although we have it constantly at hand so that it is more ours than are the individual facts of nature.

"All this has often led men to attribute knowledge of this kind to an entirely different source, namely to view it as existing *a-priori* in us (previous to all experience). That this opinion is untenable was fully explained in our discussion of the achievements of Stevinus. Instinctive knowledge, is after all, only experimental knowledge, and as such is liable to prove itself utterly insufficient and powerless when some new region of experience is suddenly opened up."[10]

Archimedes, true to Greek tradition, sought to give the principles of statics a higher measure of validity by deriving them from the axioms based on *a-priori* or instinctive knowledge. Appeal was also made at critical points to the principle of symmetry

[9] DUHEM, "*Origines de la statique*," Vol. I. p. 303.
[10] MACH, p. 83.

because our perception of the equivalence of symmetrical arrangements is instinctive. The application of the methods of geometry thus tended to emphasize demonstrations which were needlessly long and intricate; in reality the validity of one proposition is not increased merely by referring it back to other equivalent observations.

The experimental method really rests upon a different concept of truth. It acknowledges that each "new observation and perception are (*sic*) of equal rank with *every former one*—that it is derived from *the same* source of experience."[11]

We have no evidence of any general acceptance of such a position during antiquity. Experiments were made, as has been suggested, but the concepts of truth were antagonistic to any general adoption of the experimental method. The work of Strato in experimental physics, which inspired the passages of Hero cited herein, exerted considerable influence upon several of the sciences, but its achievements were restricted to the correction of certain details of the early Peripatetic philosophy. The doctrine that the vacuum was impossible was restated in the form that persisted through the Middle Ages—nature abhors a vacuum. The immediate results of the application of a revolutionary method were thus small enough.[12]

III

In addition to the treatises upon pure theory there was a considerable body of writing on applied science, to some of which reference has already been made. Besides these treatises there was a body of tradition which is scarcely known to us, though recent study has discovered some evidence of the quality of this practical knowledge. For the purposes of a study of the relations between pure science and invention, these treatises and the records of their writers are especially important. Unfortunately, our knowledge of the authors of the treatises is scanty, and their dates almost wholly unknown.

Archimedes, though primarily concerned with the most rigorous application of pure theory, was a talented inventor. The devices constructed by him during the siege of Syracuse threw the invaders into such terror that direct attack was finally abandoned and the

[11] Mach, p. 81.

[12] Diels, "*Antike technik*," p. 27.

siege converted into a blockade. Besides these engines of war, various other inventions are credited to Archimedes, though without very decisive proof of the accuracy of the statements. The famous water screw is presumed to have been in use in Egypt prior to Archimedes, but no details are really known. Archimedes was thus an engineer and an inventor as well as a scientist; but he left no writings on practical subjects and we are told by Plutarch that this discrimination against practical mechanics was due to the low esteem in which such matters were held. However true this may have been in his case, treatises of a practical character begin to appear at about that time. Ctesibius, Philo of Byzantium, Atheneus, Hero of Alexandria, Marcus Vitruvius Pollio and Pappus of Alexandria, devoted attention to the description of machines and apparatus and to the needs of practical mechanics and military engineering. These treatises on mechanics rose distinctly above the level of empiricism and at their best represent a substantial attainment. They are especially important for the history of invention.

The treatises on military engineering are also important. The emergencies of war create new problems that are severe tests of mechanical facility, and apart from the industrial effort devoted to military apparatus the principles involved may become important either to the advancement of science or to the development of the purely industrial arts. Furthermore, in the emergency of war, cost problems are neglected. Apparatus capable of meeting a particular need will be built without much regard to costs. This obstacle to industrial innovation is thus much diminished. From these sources we may best measure the precise significance of the accomplishments of science. From such material, too, we may appreciate the influence of practical, empirical development in extending the field of experience. Missile weapons, geared mechanisms, and pumps of various kinds involved mechanical problems that passed definitely beyond the range of early theoretical analysis. When these devices had come into such general use as to enter into the body of general experience, new problems were set for scientific analysis and in their solution new methods and new principles were necessarily called into play. Careful consideration of the scope of these treatises of antiquity will emphasize the curious limitations both of direct scientific accomplishment and of concrete mechanical experience.

Our knowledge is, of course, affected by the loss of a portion of the literature, but these losses are not proportionately more serious than in other fields. There are also considerable difficulties in establishing the dates of the various writers in the field. The general sequence of the primary works can be deduced from the references in the texts, but the lives of the writers have left so little trace in the records that no one of even the primary authors can be identified with certainty with any single century. Ctesibius is placed by some in the third century B.C. (about 287–247 B.C.), by others in the following century (170–119 B.C.) Philo of Byzantium is supposed to be the pupil of Ctesibius, so that his period must share this uncertainty. Hero of Alexandria was at one time also supposed to be a pupil of Ctesibius, and thus given an early date. References in the texts of Hero make it difficult to assign any date prior to second half of the first century B.C. Some writers now identify Hero with the later part of the second century [13] A.D. but such a view is not easily supported. Vitruvius is ascribed with reasonable certainty to the last half of the first century B.C. There are no cross-references between Hero's works and Vitruvius so that it is necessary to presume that they were near contemporaries or sufficiently isolated by distance to keep their works distinct. Even with the earliest date, the more general treatises on applied mechanics would follow the primary achievements in theoretical mechanics, and as Hero is presumed to be identified with the Alexandrine school of the early Empire the most substantial series of works is roughly associated with great critical revision that gave Greek science its final form. Subsequent to Hero, there is some palpable decline in the field of mechanics. Pappus (third century A.D.) is in this branch of science hardly more than an epitomizer, and the writers on military engineering in the sixth and tenth centuries A.D. show a distinct loss of intellectual vigor. The last of these writers, Hero of Constantinople, is important to the student chiefly because the texts are accompanied by drawings which are invaluable in the study of the general problems of reconstruction.

The losses suffered consist mostly of early treatises or portions of treatises supplanted by later works. Thus, we have nothing of Ctesibius himself. The portions of Philo's work supplanted by Hero are lost. Enough is left to afford a fairly comprehensive

[13] TITTEL, in Pauly-Wissova, "*Real-encyclopedie*," gives the dates 150–250 A.D.

survey and to give some sense of the extent of development between the fourth century B.C. and the beginning of the Christian era. Recent studies of the inscriptions on the arsenal at the Piræus have shown that definite building rules existed for the proportions of buildings and that formulæ existed for determining the proportions of beams and columns. These were not then reduced to writing, though some of these matters might be included among the problems of statics. The extent of the purely oral tradition can thus be controlled in some measure from archæology.

A brief description of the final accomplishment is desirable, though it involves many elements of hazard. There are full descriptions of the five simple machines: the lever, the wheel and axle, the pulley, the wedge, and the screw. The principles of statics were sufficiently apprehended to make it possible to compute the approximate mechanical advantage of the simple machines and their primary combinations. The theory of computation seems to have been carried somewhat beyond the usual limits of practical application. It is not clear that computations were accurately worked out for the wedge and the screw, though enough was known to meet primary practical needs. The notable practical achievements of Archimedes lay in the mathematical computation of the mechanical advantages of the various machines and their combinations. The tradition was developed, reduced to writing, and applied to various devices by Philo of Byzantium and Hero of Alexandria. Vitruvius was in contact with the tradition, but his text is disorderly and there is no evidence of a clear understanding of the principles involved. The mechanics of Hero, on the contrary, are a brilliant accomplishment. The exposition is orderly and, within its limits, comprehensive. The treatise is a perfectly adequate guide to the understanding and use of these machines and their simpler combinations. Despite the analysis of trains of geared wheels, there are grounds for presuming that the use of such trains of mechanism was not common at that time.[14]

[14] The full range of Greek work is adequately indicated by the list of works that can be ascribed to Hero of Alexandria with substantial certainty. In the field of the principles of geometry, optics, and surveying we have: a commentary on the elements of Euclid, now largely lost, the "*Metrica*," the "*Dioptra*," the "*Katoptrica*." In the field of general and theoretical mechanics, we have: the "*Mecanica*" or "*Baroulkos*." In the field of applied mechanics, we have: the "*Belopoiika*," the "*Cheirobalistra*," the "*Pneumatica*," the "*Automatopoiika*," lost treatises on water-clocks on the construction of bal-

The elements of surveying and civil engineering were effectively understood and apparatus had been devised to admit of the achievement of a significant degree of accuracy. The general tradition in this field was very old, as the Egyptians had developed practical geometry to quite a degree. Both their theory and their instruments were defective and it was the work of Greek science and invention to overcome these difficulties. The achievements in pure geometry and mathematics were of course the foundation, but the technique of practical observation was equally important. The final achievement is embodied in Hero's treatises on measurements and the dioptra. Subject to ultimate improvement in accuracy by the addition of lenses, the dioptra was capable of any work in surveying, and as the essential principles were clearly perceived, we have no grounds for supposing that complete competence was not achieved or achievable by Hero's time. We are hardly in position to judge accurately the extent of his individual contribution.

The great accomplishments of Greek mechanical science lay in these fields, as one passes to other problems the maturity and competence of the work diminishes perceptibly. All else that could be called mechanical science was included in the large field of pneumatics. There was some accomplishment of a scientific character. The elementary principles of hydrostatics were known. The operation of siphons and vacuum pumps was understood after a fashion, but so incompletely that the Greeks never achieved more than the simplest type of vacuum pump despite the great practical importance of such devices for raising water. Various phenomena of pressure in liquids and gases were perceived and known in a practical way, but without any genuine appreciation of the fundamental principles involved. The pressure of the atmosphere was not explicitly recognized. This is not to their discredit, but lack of such knowledge set limits to possible achievement. The scientist was not in a position to redefine the experience of the craftsman. This is rather striking in the treatises of Philo and of Hero on pneumatics. The siphon appears in every possible form and combination. There are simple contrivances to utilize the expansion of heated air or steam, or for the utilization of water pressure. In the entire list of the devices, applications of

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ances, and on arches. In the field of practical mensuration, we have: the "*Definitiones*," the "*Geometria*," the "*Geodesia*," the "*Stereometricorum collectio altera*," the "*Mensurae*," the "*Liber geoponicus*," the "*Mensura trianguli*."

nearly all the essential elements of machines appear. A similar empiricism appears in the work of the military engineers. The more notable machines are the cross-bows and catapults which embody applications of the simple machines to enlarged bows or slings. In all this work one sees for the most part the direct achievement of an immediate end by clever manipulation of concrete things. The inventor seems to be working mainly in the field of perception rather than in the field of the imagination. At all events the influence of science had not then proceeded to sufficient lengths to suggest remote ends.

IV

Diels, a notable student of the technique of antiquity, expresses surprise at the lack of interest shown by the Greeks in technical inventions and in the personalities of inventors. He complains of the indifference shown even to the names of the military engineers whose participation in sieges and campaigns makes the omissions less comprehensible. "The historians, as well as ancient society in general, undervalued the technologists."[15] This view is very commonly held, and is frequently expressed in a much more extreme form. Some writers imply that there was a positive deflection of effort into other channels and that therefore the technological accomplishments of a practical character were less substantial than they might have been. These allegations are commonly supported by reference to the aristocratic organization of society and to the large use made of slaves. With slave labor easily accessible labor-saving devices were not necessary and therefore there was little interest in inventions.

This general attitude toward these technological problems is likely to close our eyes to many important aspects of economic and social history. There is danger that we should look for the kinds of technical achievements that are the striking features of the early modern period. The great extensions in the application of power and the generalization of relatively automatic mechanical devices make striking differences in the detail of industrial life and organization. Such changes, however, are the result of long processes of striving towards remote ends. When technological advance involves only a slow accumulation of relatively small changes in the methods and traditions of craftsmanship, the individual inven-

[15] DIELS, "*Antike tecbnik*," p. 29.

tion is not a striking achievement. It appears as an "improvement" rather than as an "innovation," and most of the individual changes would doubtless reveal their full meaning to general perception so that they would not seem to possess any element of mystery. At the level of perception the process of invention is not particularly impressive. It is merely part of a developing craft tradition that is felt merely as "tradition." The changes are accepted without much conscious realization of the novelties involved. At such a stage in technological development "invention" would not attract much attention, even if there were no obstruction in the general attitude of such a society. Early society tends to be oppressed by tradition, and not even the vigorous rationalism of Greek philosophy could do much more than transform the reverence for immemorial custom into a deep respect for eternal truth. It is strictly accurate to say that such a society is not "interested" in technological change, and probably correct to say that technological advance is undervalued, though this last statement is hardly so safe. The value of inventions is more justly appraised than appears on the surface.

It is not difficult to understand why so few inventions were recognized as such, and identified with some specific personality. These outstanding achievements are the index of the transfer of the work of invention from the field of perception to the field of the imagination. They were perhaps no more important than many others, though they commanded more attention. We hear a good deal about the water clock and the organ, though the names of the inventors of the water mill are wholly unknown. This is partly due, perhaps, to the caprice of record making, more largely, however, to differences in the processes involved in the invention and in the diffusion of knowledge of the accomplishment.

The recorded inventions represent only a modest portion of the substantive technological advance in antiquity, and it is essential to our present purposes that the fact should be recognized though it is impossible to attempt any formal discussion of the technical advances prior to the last century before the Christian era. The literature is abundant and the magnitude of the changes beyond possible doubt. The tradition as developed in the Mediterranean world must be followed back to Egypt and Mesopotamia, for much of the craftsmanship and technology of Greece and Rome is derived directly from the great river cultures, most especially from Egypt. The development in many fields can be readily

followed, notably in the technique of building, the handling of weights in general, the raising of water, fighting fire, mining, the extraction of oil and wine, and missile weapons.

Although positive contributions of substantial moment were made by Arabic scholars in many fields, little was added by them to the Greek tradition in the field of the mechanical sciences. Their great achievements lay in other fields. No originality was shown by the Byzantine Greeks at Constantinople. Neither group did much more than edit or translate the older writings. The primary treatises in both pure and applied science were kept available; but of the two groups the applied science fared the worst, if we may judge by the rather small number of Mss. of the extant treatises. Thus, there is no complete Greek text of Hero's mechanics, and only one Arabic version, now represented by four Mss. No doubt this is due in part to the importance of oral tradition in the transmission of practical knowledge: the treatise on practical science was less necessary. It is rather odd that no Latin translation was made of the Arabic version of Hero, but this may be due to similar circumstances, and it is more than likely that Hero was practically outgrown by the time of the Latin renaissance.

V

From the Latin renaissance to the last half of the fifteenth century, systematic writing in the field of the mechanical sciences was confined to small but important additions to the theory of statics. Isolated descriptions and drawings of mechanical appliances occur, and by the beginning of the fifteenth century there was some little writing on the problems of military engineering. These writings have been preserved in part and a few of them have been carefully studied, but they can hardly be described as systematic treatises. At the best, they are disconnected descriptions of individual pieces of apparatus. Some of them are mere jottings for the use of the man himself. None of them approach in compass or quality the Mss. and early printed books of the late fifteenth century. As regards practice, therefore, one must assume that direct oral transmission was the primary factor in the perpetuation and diffusion of craft skill and all manner of technological proficiencies. The only records of medieval practice are the casual drawings and illustrations in Mss. and the surviving instruments of the various crafts.

In pure science, the propositions of dynamics were still dispersed through the general body of philosophy. Any description of the status of the tradition would be out of place in this connection as the discussion centers about the problems of astronomy. It is important to note, however, the persistence of doubt and controversy. The Ptolemaic system was dominant, but it was not accepted without reserve. A portion of the heliocentric literature survived, and the difficulties of the Ptolemaic system themselves provoked a large volume of discussion. It all seems sterile to us because it was inconclusive, but the presence of these doubts must be recognized in any attempt at historical treatment because they modify in so many ways the attitude toward the Peripatetic tradition. The modern scientific spirit is the outgrowth of these overpowering doubts.[16] Out of the conflict grew new concepts of the problems of science. By curious and almost imperceptible stages the conviction grew that true knowledge of the nature of things could be secured only by critical consideration of systematic observations and experiments.[17] The application of a rigorous logical method thus proved in the end to be fatal to reliance upon intuition and its axioms, and the prolix controversies of the thirteenth and fourteenth centuries gave birth to experimental science.

Most of these discussions, however stood outside the mechanical sciences, and in the specific domain of mechanics constructive work was confined to the elaboration of the treatises on the balance. The results were not large or conspicuous, but they exerted a real influence on the development of these sciences and enable us to appreciate more exactly both the achievements and the background of Stevinus and Galileo who were long presumed to have made the first formulations of the modern principles.

Recent studies show that the mechanical sciences were not wholly excluded from the active development of the later Middle Ages.

"In the Middle Ages, statics was taught in two ways: in the universities, the masters of arts attached the study of the laws of equilibrium to the commentaries with which they enriched the cosmographic treatises of Aristotle; outside the universities, statics was treated as an independent mathematical science without contacts with philosophy. This science was found in works attributed specifically at times to Euclid, Archimedes, or Jordanus, but more

[16] DUHEM, "*Notion de théorie physique; Systéme du Monde*," Vols. III–V.
[17] DUHEM, "*Notion de théorie physique*," pp. 34–35.

frequently designated by the collective term, "authors on weights" (*auctores de ponderibus*)."[18]

The "Jordanus" enumerated among the "authors on weights" presents certain ambiguities. Although a specific individual is commonly identified with the treatises that bear that name, Duhem finds that there are three distinct versions of the treatise on statics, so different in quality, method, and scope that we must presume them to be the work of more than one man. In this event, the earliest of the treatises cannot be satisfactorily associated with the Jordanus the Saxon who entered the Dominican order at Paris in 1220, and in fact the literary activities of "Jordanus" seem rather surprising. Duhem seems inclined to attribute the earliest of the three treatises to an unknown Jordanus. The second might conceivably be identified with Jordanus the Saxon, while the third is the work of an author who cannot be identified at all. This personage is called by Duhem "the precursor of Leonardo."[19] For brevity of reference the treatises may be designated as "Jordanus" I, II, and III. As a result of the organization of medieval teaching these treatises were grouped with the treatises of antiquity, and for convenience several treatises were frequently bound into a single volume. Because of the weakness for names and historical sequence the state of the Mss. affords little clue to their origin and even in the early printed editions the texts were not adequately distinguished. Historical development was further obscured by the fact that the existence of a text of "Jordanus" I was long unknown. Both the other texts were printed, but "Jordanus" III was so badly edited that it is well-nigh incomprehensible.

"Jordanus" I is manifestly based on the Aristotelian treatises, but it points out the way to new achievements by attempting much more general formulations of the fundamental principles. The discussion of the stability of the lever in various positions amounts to a significant redefinition of the problem, and though the solution proposed is defective the analysis of potential displacements is suggested. "Jordanus" II is wholly different in scope and point of view. The philosophic elements in statics are more in evidence and the discussion follows the classic models very closely. The author displays less knowledge of geometry and less skill in logic than the author of "Jordanus" I. Despite long currency this was

[18] DUHEM, "*Origines de la statique*," Vol. II, p. vi.
[19] DUHEM, "*Origines de la statique*," Vol. I, pp. 99–108.

the least valuable product of the French school of the twelfth and thirteenth centuries. As it was long the best-known of the treatises, it is scarcely surprising that the work of the school was misjudged.

"Jordanus" III is divided into four books in the Mss. The second book contains almost nothing original, being largely drawn from a late Peripatetic treatise on the lever. The fourth book summarizes the Aristotelian system of dynamics, with appreciable change. The first and third books, however, contain much that is new and significant. For the first time, the analysis of the lever overcomes the naïve error of thinking in terms of forces conceived as acting at right angles to the lever arm. The dominance of this particular error of perception is strange, for the balances in daily use were equipped with baskets which were freely suspended from the lever arm and thus exerted their pulls at varying angles. Hero very nearly reached a correct view of the problem, but without clear apprehension of the consequences of his demonstrations. Some of the problems given in "Jordanus" III are taken from "Jordanus" I, but the demonstrations are new.

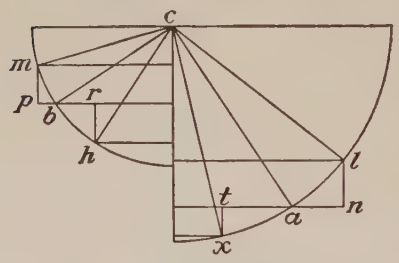


FIG. 2.—Demonstration of the bent lever. Jordanus, III.

"A balance (Fig. 2), has two unequal arms *ca* and *cb*, which are set at an angle to each other; the two points *a*, *b* are equidistant from the vertical line dropped from the point of support *c*; the arms carry equal weights; is the balance in equilibrium or not?

"Jordanus" I had treated this problem, or at least a special case of this problem; he had concluded that the balance would not be in equilibrium under such conditions and that the weight carried by the shorter arm *cb* would raise the weight carried on the longer arm *ca*.

"The Precursor of Leonardo, on the contrary, gives the correct answer to the problem; the balance will be in equilibrium. But he is not satisfied with the mere statement of the solution, he supports it with a most remarkable demonstration.

"On either side of the arm *ca*, two lines are drawn making equal angles with *ca*; similarly on either side of the arm *cb*, lines are

drawn *cb*, *cm* making equal angles with *cb* and also equal to the angles drawn above.

"This done, he inquires if the weight *a* can raise the weight *b*; and he declares that this is impossible. In that case the arms of the lever, *ca* and *cb*, respectively, would assume the positions *cx* and *cm*. The weight *a* descending the distance *tx*, would raise the weight *b*, which is equal to it, the distance *pm* which is greater than the distance *tx*. Similarly, the weight *b* could not raise the weight *a*: for the arm *cb* would move to *cb* while the arm *ca* would go to the position *cl*. The weight *b* in descending the distance *rb* would raise the equal weight *a* through the distance *nl* which is greater than *rb*."[20]

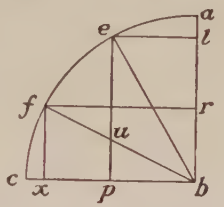


FIG. 3.—Demonstration of the moment of force. Jordanus, III.

The principle is stated in a somewhat more general form in another place.

"If a weight is raised, and if one knows the length of the support, the weight of the load can be determined for any position . . . The weight of the load supported at *e* by the support *be* (Fig. 3) will be in the same proportion to the weight sustained at *f* by *fb* as *el* is to *fr* or as *pb* is to *xb*. The weight placed at *e* on the extremity of the lever *be* will weigh the same as if it were at *u* on the lever *bf*."[21]

To these demonstrations must be added the solution of the problem of the inclined plane. It is, however, an application of the principles and methods involved in these other problems, so that it can hardly be necessary to review the solution in detail.

The two historians of science who discovered "Jordanus" III may perhaps exaggerate in a measure the importance of their find, but for the moment these are the only professional statements on the subject. Giovanni Vailate of Turin says:

"To find a treatise in which the principles are so thoroughly based upon the doctrine of potential displacements (*travail virtuel*), even if the doctrine is only partially and imperfectly conceived . . . one must pass on to the little treatise which Descartes entitled '*Explicatio machinarum atque instrumentorum quorum opu gravissima quaeque pondere sublerantur;*' that treatise is in fact the first attempt, subsequent to the treatise of which we are speaking,

[20] DUHEM, "*Origines de la statique*," Vol. I, p. 141.
[21] DUHEM, "*Origines de la statique*," Vol. I, pp. 143–144.

to establish the whole science of statics upon the foundations embodied finally in the 'Analytical Mechanics' of Lagrange."[22]

Duhem says:

"This principle (of Jordanus) is the true origin of the method of potential displacements whose amplitude and power is the admiration of all modern physicists. Born of the meditations of 'Jordanus' (I) and of the Precursor of Leonardo da Vinci ('Jordanus' III), it was developed in the works of Leonardo, Guido Ubaldi, Galileo, Robertval, Descartes, Jean Bernouilli, to achieve its final expression in the writings of Lagrange and J. Willard Gibbs."[23]

The foundation of modern statics must thus be carried back to the close of the twelfth century or the latter part of the thirteenth century according as "Jordanus" I or "Jordanus" III is chosen as the founder. Properly speaking the distinction belongs to the anonymous author "Jordanus" III. The development of the scientific achievement is thus a consequence of the Latin renaissance, which was actually obstructed in some measure by the subsequent study of the Greek texts of Archimedes in the sixteenth century. The misconception of the actual course of development was revealed only by the thorough studies of the manuscript sources by Vailate and Duhem. The students of the Greek texts deemed them intrinsically superior to the medieval treatises and the publicity achieved by the newer school, nobly supported by the printing press, obscured for the moment the accomplishment of the medieval scholars.

The accomplishments of medieval scholars in the other branch of statical theory was not of comparable magnitude. Albert the Saxon (fourteenth century) redefined a number of problems connected with the relation of the position of the center of gravity to the equilibrium of objects, but his solutions were incomplete. This train of thought led ultimately to Torricelli's proposition: "A heavy body, or system of heavy bodies, whose center of gravity is as low as possible is certainly in equilibrium."

In the Peripatetic philosophy every body had its "natural" place and was in equilibrium when it occupied its natural place. A number of interesting propositions and difficult questions arose when the doctrine was applied to the earth as a whole. Aristotle reached the conclusion that the earth must be spherical, for other-

[22] DUHEM, "*Origines de la statique*," Vol. II, p. vi.

[23] DUHEM, "*Origines de la statique*," Vol. I, p. 147.

wise the various points on the surface would not be equidistant from the center. It was not so easy to understand why a portion of the surface should be occupied by water and a portion by land. Arguing from the influence of gravity upon a stone cast into the water, it might be expected that all the land would sink to the bottom of the oceans and that the surface of the globe would be exclusively occupied by water. Without going far beyond the older solutions of these problems Albert the Saxon applied throughout the concept of a center of gravity, which had commonly been applied only to relatively small bodies. He thus transformed the classical doctrine of natural position in a number of respects when he restated it. He held that the earth was in its "natural" position when its center of gravity is at the center of the universe. He distinguished the center of gravity from the center of the mass, and in this way explained the division of the surface of the earth between land and water. Land he held to be of varying gravity so that the center of gravity would be lower than the center of the mass. Hence the center of gravity of the land hemisphere would be lower than the center of the earth, and water would therefore flow to that side of the earth which was nearest to the center of gravity. He repeated the older demonstrations of the sphericity of the earth with some additions.

The important contribution of Albert the Saxon lay in this revision of the older notions of the direction of the lines of gravitational force. The older philosophers had held that the center of the universe was at an infinite distance and that the lines of force were parallel. Albert the Saxon conceived the center of gravity to be terrestrial and reasoned correctly in applying generally the arguments which were commonly applied to the special case of the shape of the earth's surface. This doctrine was summarized in the form of a number of corollaries, of which the first two are the most important.

"1. Because the earth is round, it follows that lines normal to the surface of the earth converge toward the center when they are prolonged.

"2. It follows that if one constructed two vertical towers, as they were raised higher, they would come to be more distant from each other, whereas the distance between them would diminish in proportion as the points of measurement approached the bases. [Conversely] if two towers were built whose walls were exactly parallel, there can be no doubt that they would fall in upon each

other, if construction were carried on at an equal rate in the case of each of the two towers."[24]

The erroneous conclusion was perhaps the most fruitful aspect of the whole discussion, for in the attempt to correct this mistake, Leonardo da Vinci was led to a correct formulation of the problem of equilibrium.

VI

Although the medieval scholars took steps that were of genuine significance, the importance of their work in the mechanical sciences was very imperfectly revealed by their writings. It was not enough that these fundamental propositions should be enunciated. No large development of mechanics would be possible until the consequences of these principles were fully appreciated. Although this seems to be a simple step it involved the realization of the need of an entirely new synthesis based upon formal experimentation. The new primary concepts necessarily involved a recognition of the inadequacy of general experience as a foundation. The principle of the lever ceased to be the intuitively perceived relations of the lever in a horizontal position. The concept of gravitation was raised above the level of the naïve concept of "natural" positions. The more sophisticated formulations of the primary principles thus invited the application to the mechanical sciences of the experimental methods whose necessity in physics had long been apprehended as a matter of abstract principle, especially by the Averroists in Italy.

The beginnings of the new synthesis are to be found in the notebooks of Leonardo da Vinci. It is only with him that isolated propositions cease to be extensions of the old doctrine in particular cases and become a part of a distinctly new approach to the entire problem. Characteristically, none of the scientific work of Leonardo was finished to the point of being a maturely composed treatise. Three treatises were indeed put together during his lifetime; the treatise on painting, the treatise on the nature, weight, and motion of water, and the treatise on the flight of birds. These works, however, consist of various notes, sorted, and roughly put together without strict regard to continuity of thought. They are thus preliminary drafts rather than maturely pondered compositions. Beyond these, we have only the notes which would ultimately perhaps have been worked up into a series of treatises. The scope of his thought is partially indicated by the titles of the projected works. He speaks of the following: the book on motion,

[24] DUHEM, "*Origines de la statique*," Vol. II, pp. 47, 80.

the book on impacts, the book on weights, the book on moments of energy, the book on the principles of machinery. His work was thus a vast project, whose full accomplishment involved the work of many successors.

When the scope of the Mss. first became generally known towards the close of the eighteenth century, the interest of their contents was qualified by the difficulty of imagining how this work could have exerted any genuine influence upon the actual development of science. It is easy to forget that the world of Leonardo's time was not wholly emancipated from general dependence upon Mss., and thus the world of the nineteenth century was prone to assume that Mss. could not circulate. Internal evidence together with the actual history of the Mss. have made it clear that the Mss. were circulated rather extensively. The entire mass of Mss. were left to the care of Francisco Melzi the secretary and friend of Leonardo. In order to enhance the fame of his master, Melzi permitted copies to be made of various Mss. and with some restrictions allowed various artists and scientists to use the collection. After Melzi's death his heirs were less concerned about the preservation of the collection intact. Some volumes were sold, some were given away, some were stolen. Leonardo's work was thus of direct influence for not less than two generations.

Among the scientists allowed to delve in this fertile source of inspiration was Jerome Cardan, a Milanese of genuine talent and of a rather acquisitive disposition. Most of the theories of Leonardo in the field of the mechanical sciences, thus appeared in print in an organized form in the two substantial treatises of Cardan: "*De subtilitate,*" *libri* xxi; "*Opus novum de proportionibus.*" It was in this form, that the work of Leonardo came to exercise its most notable influence upon the early development of the mechanical sciences.

The most decisive innovation was the introduction of systematic experimentation. This mode of inquiry is in evidence at every turn; sometimes incidentally, sometimes as a protracted search for specific formulæ. The phenomena of percussion and recoil were studied. Experiments were made with falling bodies and a formula for the acceleration was suggested. The strength of struts and girders was studied with reference to variations of length and cross-section; differences between single members and composite members were also determined. It is not easy to separate the new from the old, but nearly all this work was new in

spirit, and even if not immediately final it was by these methods that final results were achieved.

Dynamics received much attention, but the results were not decisive. The old metaphysical impediments to the effective study of motion were overcome and most of the fundamental problems were studied. His mind was reaching out to a new concept of force, and though his formulation was not wholly happy it contained important elements of truth. He made it easier to proceed with the study of the flight of projectiles, impacts, and falling bodies, though he himself achieved no final results. He was progressing towards a formulation of the principles of the composition of forces, but there is much doubt as to the exact nature of his accomplishment. There is always a danger of our reading later knowledge into his notes and diagrams. In this whole field one fact is patent: all the important problems were redefined by Leonardo's efforts, and reduced to forms which made solution possible. This in itself is no mean achievement. As the solutions of the primary problems of principle were not achieved until rather more than a century later, we may readily judge the difficulties that remained. Leonardo defined problems of dynamics that were adequately solved only through the efforts of Galileo and Huygens.

In the field of statics, the achievements of Leonardo were less novel but more complete and finished. All the primary problems and concepts were derived from the medieval writers, most especially from the school of Jordanus and the work of Albert the Saxon. Under his hands, the rather imperfectly apprehended principles become a system of thought which carried Leonardo far. The work of the school of Jordanus was developed until all the primary theorems were clearly enunciated and the scope of mathematical calculation in mechanics greatly extended. The propositions and corollaries of Albert the Saxon were elaborated, and a correct solution was given for the equilibrium of a body. As long as the center of gravity is not projected beyond the base of a body, the body remains in equilibrium. Otherwise it falls in the direction of the heavier part. The doctrine of the center of gravity had thus carried him definitely into the boundaries between statics and dynamics. Furthermore, speculation along the lines of these problems and principles led Leonardo to adopt the heliocentric hypothesis as early as 1508. This is significant only as an index of the intellectual temper of Italy at that time, for Copernicus had

already begun work upon the problem largely as result of the stimulus of contacts with Italy. The incident affords an interesting illustration of the vast consequences involved in problems that would scarcely seem so suggestive and fruitful.

The substantive achievement was clearly of limited extent, but if we consider the relation of this progress to the process of invention it is noteworthy that the imaginative elements were rapidly becoming dominant. In Leonardo's time, if not before, the character of problems considered by inventors underwent a substantial transformation. Work was directed towards more remote ends; scientific principles were applied on a larger scale; much of the process was transferred from the field of the perception to the field of the imagination. Without better knowledge of the notebooks and treatises of other engineers of the fifteenth century, we cannot be sure that this change had not taken place prior to Leonardo's time. Leonardo's notebooks, however, contain indisputable evidence of the extent of the change in his own mind. The nature of the record is itself conclusive. Sheet after sheet is covered with drawings and sketches: sometimes of apparatus already built and in use; quite as frequently concerned with devices that never existed outside of Leonardo's mind. In many instances, it seems to be clear that no model was ever constructed. Leonardo, therefore, had achieved the power of thinking freely in terms of mechanism. This mechanical mindedness did not exclude the human body. His anatomical drawings are concerned not only with forms and physical details but quite as definitely with the mechanical problems. He thinks of muscles in terms of their relation to the bones as to levers. Human and animal structure, thus, has mechanical implications as well as forms and proportions. The notebooks are thus a priceless treasure for the history of invention. Here we see many a later invention expressed as pure concept. We may be sure, that it was not the first time in history that such things had been done. Perhaps Villard de Honnecourt, the French architect of the thirteenth century, had achieved some powers of abstract mechanical thinking. Perhaps, the military engineers of the latter fourteenth and early fifteenth centuries had reached such a stage. Further study should yield significant results: at present, we are entitled to say that Leonardo had clearly achieved these powers of the creative imagination that have played such a part in the technical transformation of the modern world. We are thus entitled to say that the large development of imaginative thinking

precedes the full accomplishment of the formulation of the principles of the mechanical sciences. Many of the actual accomplishments required positive scientific knowledge, and in such cases realization of dreams, hopes, and aspirations was inevitably postponed: in general the imagination of inventors outstripped the analytical work of pure science. Much apparatus was conceived long before there was any effective possibility of making it, and the tone of struggle and frustration that appears in the lives of the inventors of the sixteenth and seventeenth centuries may be largely explained by the degree to which their power to conceive had outstripped their power to give material substance to their dreams. It is in this period, therefore, that the general process of mechanical achievement assumes its modern form of an eager striving towards remote ends.

With Leonardo the early history of the mechanical sciences came to an end. In rather less than two centuries the mechanical sciences were given their modern form through the efforts of notable men in all the leading countries of Europe. Italy, France, Germany, England, and the smaller countries of the north all made substantial contributions to the final result, and though the international quality of the achievement was not at all times keenly felt the contacts were sufficiently extensive to make the international element a significant reality. The major scientific accomplishments of the sixteenth century lay just outside the field of mechanics, but the following century was marked by an extraordinarily rapid development.

The phenomena of falling bodies were studied by Galileo by experimental methods which display great ingenuity, especially in the contrivance of apparatus for the minutely accurate measurement of time. The finality of his formula is an index of extraordinary powers of observation and reasoning. The publication of his results in 1638 thus marks the final break between ancient and modern dynamics, and as Galileo extended his experiments and analysis to all problems of dynamics connected with single bodies, he was able to establish secure foundations for the work of successors. The studies of the flight of projectiles and the preliminary study of the pendulum were of particular significance to the mechanical sciences. Although his work with the pendulum was restricted to its relation to the general principles of falling bodies, he was quick to perceive the importance of the pendulum as a means of accurately controlling the movement of a clock.

The completion of the work on the pendulum, however, was due to the analysis by Huygens of the phenomena of circular motion. This highly complex phenomenon, so long regarded as "simple," was resolved by him into a combination of centrifugal and centripetal forces whose intensities and accelerations were successfully reduced to generalized formulæ. These studies led Huygens to the pendulum by a new route. Galileo had approached the problem as a case of a body moving down an infinitely small inclined plane. Huygens attacked it as a particular case of circular motion, and succeeded in working out the primary formulæ though not with great economy of effort in his demonstrations. This work furnished the incentive to further work on the clock and Huygens' concepts were put into practical use within a few years of the publication of his notable treatise in 1673.

During this same period fundamental work was also being done on the problem of the vacuum. Down to the time of Galileo no progress had been made beyond the doctrine of Strato (*c.* 288 B.C.) and Hero that nature abhors a vacuum. The impulse to inquire further into matters was furnished by the inability of a vacuum pump to raise water more than 32 feet. It was evidence that the abhorrence of nature was a measurable quantity, and Galileo made some inconclusive attempts to determine the exact amount of effort exerted by nature. The phenomenon was explained by Torricelli and further demonstrated with mercury by Viviani (1643) in pursuance of a suggestion from Torricelli. The experiment came to Pascal's attention without details, and the whole experiment was repeated by him with variations (1644). Concluding that the pressure of the atmosphere must vary according to its depth he urged his brother-in-law Perier to make experiments at the Puy-de-Dome to test possible variations at the top and bottom of the mountain (1648). The general character of the phenomena were thus established beyond doubt. General experimentation with air pressures by Guericke at Magdeburg (1650–1672) and by Boyle at Oxford (1654–1668) resulted in the formulation of the primary laws of pressure in gasses. Because of the technical superiority of Boyle's work the results are commonly associated with his name, though the work of Guericke was independent and closely parallel to his. It is scarcely necessary to point out that the full accomplishment of these results was an essential condition to the making of an effective atmospheric or

steam engine, although much study of the general problem was taking place during these years.

The initial formulation of the mechanical and physical sciences was completed by the notable synthesis embodied in Newton's "Philosophiæ Naturalis Principia Mathematica" (1686). Apart from modifications and emendations of the principles of dynamics and statics as previously stated, Newton brought together again the closely related sciences of physics, astronomy, and mechanics. But whereas the association worked out by the ancients had begun with various speculations concerning the heavenly bodies, the Newtonian synthesis began with the experimental knowledge of terrestrial phenomena and extended verified principles to the realm of astronomy. The ground had been prepared for such a synthesis by the accomplishments of Copernicus and Kepler in astronomy, and by the accomplishments of Galileo and Huygens in mechanics, mentioning only the outstanding names. The treatise of Copernicus had made an end of any genuine scientific doubt as to accuracy of the heliocentric conception of the solar system. The work of Kepler disposed of the old metaphysical assumptions of circular orbits and uniform motions. The work of Galileo and Huygens had completed the transformation of the old notion of force as a pressure in immediate contact with the object into a concept of a force that may act at a distance. It remained to generalize the concept of gravitation.

"Newton discovered first in the case of the moon that the same acceleration that controls the descent of a stone also prevented this heavenly body from moving away in a recilinear path from the earth, and, that, on the other hand, its tangential velocity prevented it from falling to the earth. The motion of the moon thus presented itself to him in an entirely new light, but withal under familiar points of view. The conception was attractive in that it embraced objects that previously were very remote, and it was convincing in that it involved the most familiar elements. This explains its prompt application in other fields and the sweeping character of its results."[25]

The studies of Huygens, rather than the famous but apocryphal apple, set the stage for Newton's great synthesis. The decisive and comprehensive character of such an accomplishment tends to destroy our appreciation of the complexity of the process that led up to it. After such an achievement the efforts that precede

[25] Mach, pp. 190–191.

come to possess *only* historical significance. Their constructive importance for the future is fully embodied in the new synthesis and the detail of the process passes quickly out of sight except in so far as some record is preserved by conscious historical effort. The great achievements of the mind tend to obscure and even destroy the evidence of the process by which they were brought to pass. From the naïve point of view only the end is significant: from the historical point of view the "end" can be adequately appreciated and known only when studied as the completion of one pattern or configuration of thought and the implicit definition of new problems for the future. In a practical fashion particular results may be utilized without full knowledge of their consequences—and in that measure it is not necessary to think in terms of a continuous process, but complete appreciation of an achievement requires knowledge both of the accomplishment and of its limitations. Full knowledge is thus thinking in terms of process; or, more briefly, historical knowledge.

Chapter IV

THE MECHANICAL EQUIPMENT OF PRE-CHRISTIAN ANTIQUITY

I

The mechanical equipment of any given society consists largely of tools and machines. In the restricted sense that is most useful for historical study or mechanical analysis, the term "tool" may best be confined to implements for the direct execution of certain kinds of work; notably cutting, striking, or rubbing. Although all tools were originally used in the hand, many have been adapted to machinery without significant change of form or purpose. The looser uses of the term are obviously due to various special circumstances which can be readily understood, but when it is necessary to deal with long periods of time there is need of precision and certainty of language.

The term "machine" presents an almost hopeless problem. Popular usage is extremely lax and the list of formal definitions cited by Reuleaux discloses a range of meaning and a laxity of expression that is hardly a credit to the engineering profession. No additional light is thrown upon the subject by the complex and confusing concepts in the famous passages of Marx's "Capital" (Part IV, Chap. XIII. Sec. 1). The carefully restricted statements of Willis and Reuleaux will serve, however, as a point of departure. Willis says:

"Every machine will be found to consist of a train of pieces connected together in various ways, so that if one be made to move, they all receive a motion, the relation of which to that of the first is governed by the nature of the connection."[26]

Reuleaux says:

"A machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions."[27]

These definitions make it possible to deal effectively with all classes of machines without inconvenience. The considerable class

[26] Cited by Reuleaux, p. 587.

[27] Reuleaux, p. 35.

of machines concerned with changing place or position does not have any specific part that can be called a tool, so that the numerous definitions which emphasize the tool as a specific part of a machine cannot be very easily applied to a crane or a locomotive. Machines designed to alter forms necessarily have tools as a component part. Emphasis on the motor is especially dangerous. Prime movers are exclusively concerned with furnishing motive power; direct actors are concerned with using motive power, but they do not depend upon any particular kind of prime mover nor upon any single mode of attachment. This distinction is especially important in any historical study of machines and inventions because the development of prime movers and of direct actors is measurably distinct. Furthermore, these definitions emphasize the existence of a long gradation of complete machines reaching all the way from relatively simple arrangements of apparatus for the use of power supplied by men or animals to complex and massive mechanisms driven by great concentrations of power from inorganic sources. The history of invention is a study of the circumstances which have converted the simple but relatively inefficient mechanisms of early periods into the complex and more effective mechanisms of today. This transformation is partly due to the character of external economic needs, partly due to the perception of modes of completing the patterns and designs of current mechanical experience.

Some of the progressive improvement of machines consists of refinements in design and execution. The parts of the machine are more and more elaborately connected so that the possibility of any but the desired motion is progressively eliminated. As the process of constraint becomes more complete the machine becomes more perfect mechanically. A grindstone, for instance, may function fairly well even if there is no specific device to prevent the stone from being lifted off its bearings by some unskilful application of force to the crank. In general, the weight of the stone is sufficient to keep it in place upon the bearings, but displacements are possible. In the terminology suggested by Reuleaux, such a machine would be described as "force-closed:" the axle is kept in place only by the downward pressure of gravity; instead of being enclosed in an appropriate case with bearings that would decisively prevent any motion but the rotation on the axis essential to the machine. "Force-closure" may also appear in a positive form, as in the case of the simplest form of pile driver, in which the weight is lifted to

the top of the guide frame and then allowed to drop freely upon the object. Reuleaux points out the generality of "force-closure" in all ancient and much medieval or early modern machinery. One important phase of mechanical development consists in the building up of constraints upon motion so that "force-closure" is finally supplanted by the interaction of pairs of mechanical elements or by long chains of interacting parts. Such a transformation results in the complete and continuous control of motion, which is embodied conspicuously in the modern steam hammer capable of forging a heavy ingot or of descending to contact with a watch crystal without breaking it. The completeness of the constraint of motion becomes in Reuleaux's analysis the criterion of mechanical perfection. Loosely adjusted and ill controlled machines are supplanted by closely adjusted machines that can be controlled minutely. Force-closure is transformed into pair- or chain-closure.

Invention, however, does more than perfect a given list of machines. Growth in mechanical proficiency results in the extension of mechanism to tasks that were not at first within the scope of any mechanism however simple. Adequate study of the origins of machinery thus requires us to consider the invention and development of some devices which cannot be included in the classes of either tools or machines. The early loom and the early apparatus for grinding cannot strictly be called machines, but they are a basis to which mechanical elements are added and after a certain stage is reached they acquire the status of machines. New machines also appear when the new devices are designed for the application of a general mechanical force to hand tools, or for the application of new kinds of force to an old machine. This general line of advance takes the form of substitutions of the more intense for the less intense forces, grading up through a long sequence that begins with types of human muscular activity that are relatively disadvantageous. For these, modes of activitity are substituted that are more advantageous and capable of minute mechanical adaptation to the purpose in hand. Then animal power is substituted for human power, and water and wind power for animal power, until finally the more intense sources of inorganic power are made available as heat energy, electrical energy, and great waterfalls are used that were long unharnessed for lack of ability to build appliances capable of resisting the pressure. To use modern electrical terminology, there is a steady increase in potential: we

have to deal with a transition from machinery worked at very low potential to machinery run at very high potential. The change in potential itself requires more and more careful constraint of motion, because these highly intense concentrations of energy could not be applied to mechanisms until adēquate control was possible. Refinements of conception and execution are thus an indispensable preliminary step to increases in potential. Power could be effectively and safely applied only in such measure as it could be controlled. Man power and horsepower were long the primary source of energy because they could be controlled by other than mechanical means.

With strict logic, the term "machine" might be applied to any contrivance in which forces are used, even if the forces are small and the actual appearance of the force is discontinuous and spasmodic. Thus, a balance or a surveyor's theodolite is recognized by Reuleaux as a kind of machine, though he is also quick to note that some departure from strict logic is probably desirable. He is willing to conform to the common usage by which the term machine "is applied only in those cases where force or motion appears continuously or to some large extent."[28] It is important to note, however, that a large number of the instruments of precision used in science and in practical affairs are in fact "machines" and present in the history of their development all the joint problems of discovery and invention that appear in connection with the kinds of machines more commonly recognized. But apart from this purely logical connection, the large class of appliances that may be called instruments of precision exert a direct and profound influence upon the development of mechanical applications, for genuine refinements of conception and execution first appear in this field. These instruments are significant to the historian both as a measure of accomplishment and as a basis of new achievements. The degree of mechanical refinement possible to any given age will be most explicitly shown by the nature and character of its instruments of precision.

II

Hero of Alexandria describes five "simple" machines "by which a given weight may be moved by a given force:" the wheel and axle, the lever, the pulley, the wedge, and the endless screw. This association of these machines in a group was based upon the supposition that they might all be computed in terms of the principle of the lever, and upon their functional relations to the

[28] Reuleaux, p. 51.

common purpose of moving heavy weights. It is possible that this treatment of the group was a feature of the lost treatise of Philo of Byzantium, but at all events it appears definitely in the treatise of Hero, and although the full text is available only in Arabic, these passages from the first half of the second Book were preserved in the treatise of Pappus of Alexandria and through him brought to the attention of the writers on mechanics in the sixteenth century. The doctrine then assumed a more general form and these machines were for a long time represented as being the primary basis of all machinery; the constituent elements from which everything else is to be derived. Despite the developments of the steam engine and various hydraulic machines, this doctrine survived far into the nineteenth century, and Reuleaux directs some searching criticism against the proposition. He maintains that, these machines are neither "simple" nor the elementary constituent parts of machinery in general.

Some light is thrown upon the historical problem by the text and title of Hero's treatise. The Arabic version bears the title: "the book on the raising of heavy weights." In Greek, the treatise bore the title "Baroulkos" (*i.e.* the "elevator") or the title "Mechanics." Although some writers are inclined to believe that there were two separate treatises under these titles, the subject matter must in that case be supposed to be largely common to both. In any case "mechanics" in Hero's time meant not the science of mechanical appliances in general, but the lifting of heavy weights. These were, in fact, the only appliances that were used with a view to the work done. Other apparatus was known, to be sure, but its utility lay chiefly in furnishing particular kinds of motion, and as the amount of force was not large it did not impress the Greek scientist as a phenomenon of the same order. There seems to be a naïve disposition to classify separately those appliances which are valued for the concentration of force. Such things are "machinery."

Hero must thus be interpreted literally. When he says, "the simple machines by which one may move a given weight by a given force are five in number" (Book II, 1.1.); these machines are to be regarded as essential parts only of the various kinds of apparatus for moving and lifting heavy weights, and with these restrictions the proposition is not unsound. These instruments are, indeed, the basic apparatus for weight lifting; they are not the constituent parts of all the machinery that has since been devel-

oped; though in Hero's time, and possibly even in the sixteenth century, there was little heavy-duty machinery that would not have come within the scope of such a generalization.

The historical significance of the error that long persisted lies in the strength of the disposition to eliminate large groups of apparatus. In the history of invention the facility shown in utilizing and controlling motion is of the utmost significance without regard to the amount of "work" done. Reuleaux shows unusual historical insight in his analysis of the beginnings of machinery, because he emancipates himself completely from the presumptions of the present day. He says:

"In taking the fire drill, in which the expenditure of force is comparatively trifling, as the first machine, we directly contradict the very popular notion that the lever occupied this position. Apart from the fact that it is by no means clear what precisely is to be understood by the term lever,—this notion shows in my opinion a mistaken idea of the way in which human capacities have generally grown, and must have grown from the first. In taking the lever as the first machine, we think of men's attempts to deal with or overcome great resistances. It is not this, however, which first attracts the opening consciousness, but is much rather the accompanying phenomenon, motion. The child shows the most lively interest in the sails of a windmill, in the millwheel and such other portions of the machinery as have distinctly regular motions: at first, however, he thinks nothing of the forces applied or brought into action by them. The separation of the idea of force from that of motion is a very difficult mental operation, and we find it occurring late and gradually. We find accordingly that the machines coming first from the unaccustomed hands of their makers are those in which forces play a comparatively subordinate part,—for they do not exceed the exertions which the worker himself makes, imperfectly conscious of what he is doing.

"This really lies at the root of the continual recurrence of the problem of perpetual motion; certain minds are always irresistibly attracted by the motion itself, by the first impression gained solely from external appearances, from the overpowering influence of which even the most accomplished cannot boast themselves to be entirely free. From attempts to cause motion the direct production of the corresponding force-actions slowly and step by step developed themselves. The popular idea which reverses the process makes the error of assuming the primitive inventor to have

been a kind of Robinson Crusoe, endowing him with a full acquaintance with modern ideas, while in reality he has both to find out the need of improvement and to recognize its possibility, before he even attempts to carry it out.

"Men certainly required an enormous period before they began to develop what might be called the motoral side of the machine,—before they attempted to use for working it other forces than their own muscular efforts. For this purpose they naturally turned first to the animals beside them, and made use of their muscles to save their own . . . "[29]

The "enormous period" to which Reuleaux refers was drawing to a close in the last century before the Christian era. Applica-

Fig. 4.—Early Egyptian swape.

tions of external forces were beginning to attract attention, and much facility was being shown in producing rather complex motions. But these beginnings which were to have such important consequences did not dominate the age, nor would they have been regarded by contemporaries as their most important achievements. Such accomplishments were interesting, useful as a means of mystifying the masses; but they appealed in the main to a different class of interests. It is undoubtedly for this reason that we find such a division of the field between the "mechanics" or the "elevator" of Hero and his "Pneumatics." It must be evident that Hero cannot be held responsible for the overgeneralization of his proposition in the sixteenth century. The five "simple" machines were to him the component parts of the apparatus for moving weights, and nothing more.

[29] Reuleaux, pp. 224–225.

The direct applications of the simple machines should not need much comment; but even here we must not take much for granted as these applications had not entirely supplanted direct labor even in such tasks as drawing water.

The lever appears in the well sweep (swape) which is to be found in Egypt as early as 1550 B.C. under the name of "shadouf," and in India, as the *picotah*, (Figs. 4 and 5).[30] It was used at Rome not only for raising water, but as an engine of war. It could be used as a weapon of offense in lifting men to attack the walls, or in defense as at the siege of Syracuse to destroy the ships of the besiegers. In various forms and modifications, the swape was used throughout Europe down to the present day. The greatest convenience of the device is for lifts ranging from 5 to 15 feet.

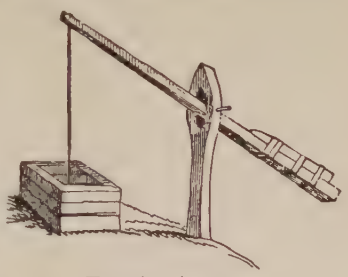


FIG. 5.—A swape.

The pulley in its simple forms had a most extended line of uses from raising water from wells to its many applications on board ship. Curiously enough, the application to wells was somewhat restricted, although it would simplify in so many ways the task of drawing water with a rope from the deep wells that were so common in Mediterranean countries. The curbs of many ancient wells are cut into so many grooves that one can only conclude that there were no windlass or pulley attachments to facilitate the use of the well. Ewbank ascribes this to the need of making the public well simultaneously available to many users. But both pulleys and windlasses were in general use by the close of the pre-Christian era.

Wedges were used extensively for splitting wood and stone, and inclined planes were undoubtedly used in much construction work. The screw appears most generally in the rather special forms of the water screw or the press, which involve some combinations with the other machines.

Both Hero and Vitruvius describe a group of cranes; having one, two, three, and four masts, respectively. These combine the lever, the pulley, and the windlass in various ways, though for the most part leverage seems to play a limited part in these devices. The detail of construction is not as well known as one would wish.

[30] EWBANK, p. 100, Fig. 40; p. 102, Fig. 43.

There are drawings in the Arabic manuscripts of Hero which seem to be rather oversimplified. The manuscripts of Vitruvius contain no drawings, and reconstructions from the text are dangerous; the plates provided by the different editors display a wide range of variation for which little satisfactory explanation is commonly available, so that many of these plates can hardly be used as historical evidence. Happily, there are some pictorial inscriptions that afford a satisfactory basis for the interpretation of the text and these justify all the essential features of the reconstructions shown by Blumner.

Fig. 6.—Crane with a single mast.

The crane with a single mast, as shown in Fig. 6,[31] is taken from the illustrations of the Arabic manuscripts of Hero, slightly retouched. The lack of tension on the supporting ropes is, of course, incorrect. As the mast is secured at the bottom by a pin, it could not be held in position without tension. The spiral on the mast is formed by winding a rope around it partly as an additional source of strength, partly to make it easier for the workmen to climb the mast to make necessary adjustments. The other aspects of the apparatus are obvious.

A two-masted crane is shown in Fig. 7,[32] interesting because of the additional appliances for increasing the lifting power of the apparatus. The form of the pulley blocks is warranted by inscriptions and the rest of the apparatus is sufficiently described in the

[31] Schmidt, "*Heronis opera*," Vol. II, 1, p. 204, Fig. 47.
[32] Schmidt, "*Heronis opera*," Vol. II, 1, p. 206, Fig. 48.

text to warrant this illustration. When the resources of power indicated here did not suffice, tread mills were used in which one or more men worked inside the wheel with the possible assistance of others on the ground outside pulling ropes. The three- and four-masted cranes could hardly have been as useful, as their range of action was less adapted to the general problems of the building trades. Various modifications of cranes are described by Hero for special purposes.

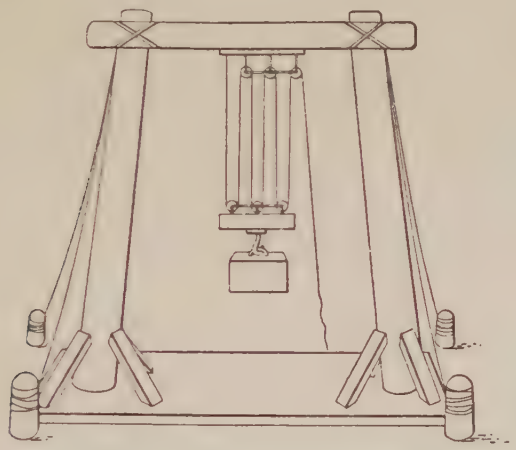


FIG. 7.—Crane with two masts.

The presses for wine and olive-oil extraction were another type of heavy-duty apparatus that was clearly regarded as a great mechanical achievement. The early methods of wine and oil extraction were based on pressures secured by the torsion of heavy ropes by means of levers. Appliances of this type appear at an early date in the Egyptian reliefs. The Græco-Roman materials indicate an active development culminating in the oil mill, and two primary types of presses—the large beam press and the smaller screw press. The oil mill and the heavy beam press had reached a fairly stable form by the beginning of the second century B.C.; the smaller screw press does not appear until the close of the pre-Christian era. All these forms remained in use for centuries with very small changes, both in wine and oil making.

The beam press appears in three primary forms which probably represent successive stages of improvement. In the simplest form, pressure is secured by loading the free end of the beam with a

heavy weight. In the vase painting reproduced in Fig. 8,[33] one of the workmen has climbed on the beam to add his weight. Presumably the weight exerts only a part of the force, for the worker on the ground is pulling. This apparatus would necessarily be limited in its development by the difficulty of raising the loaded beam, though pulleys not shown in the picture may have been used. Reuleaux presumes that the first applications of the screw were concerned with the lifting of the weighted beam rather than with direct application of pressure from the screw. The use of a weighted beam assisted by windlass and

Fig. 8.—Simple beam press.

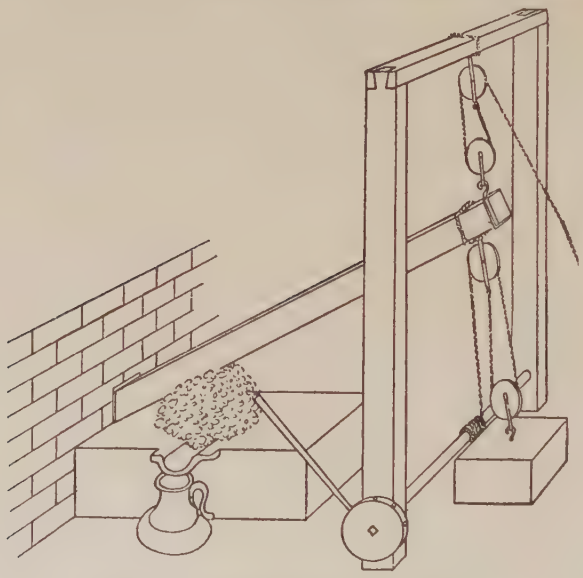


Fig. 9.—Beam press with windlass.

pulleys is attested by the description in Hero's Mechanics, Book III, Sec. 13. The apparatus is shown in Fig. 9.[34] The beam is lifted by means of the rope passing through the pulley attached to

[33] Blumner, Vol. I, p. 344, Fig. 124.

[34] Schmidt, "*Heronis opera*," Vol. II, 1, p. 227, Fig. 56.

the upper part of the frame. The weight is lifted by the windlass. The force is generated by the falling weight, subjected to some control through the manipulation of the free rope and the windlass. The rest of the drawing is schematic.

In the press as described by Cato the power was derived from a windlass worked by a long arm. The general features are shown in Fig. 10.[35] The text of Cato is interpreted in the light of various archæological remains, notably the existing remains of the press houses and the Pompeian wall painting reproduced by Blummer.

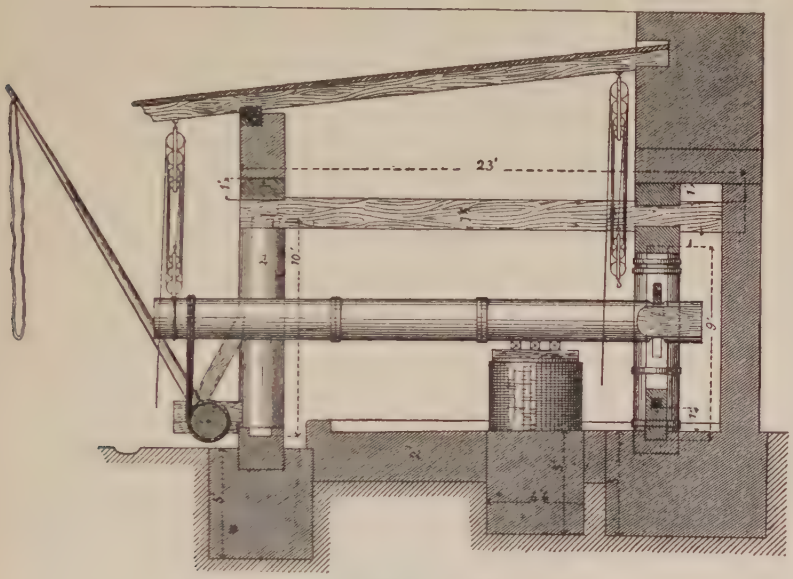


FIG. 10.—Developed beam press.

The pulleys hanging near the fulcrum of the beam are evidently used for lifting the beam to work at the press. The pulleys at the free end of the beam are used to lift the beam for the beginning of the stroke. Pressure is supplied by the winding of the heavy rope on the windlass.

The final stages in the development of this press are indicated by the descriptions in Hero, and Pliny the Elder, (23–79 A.D.). The arrangement with pulleys and windlass was difficult to manage because the ropes did not always work freely in the pulleys and there were elements of danger to the operatives through the breaking or slipping of the bars used in the windlass. The screw

[35] BECK, G. M. B. p. 79, Fig. 80.

overcame these difficulties. Although the drawing is not wholly satisfactory, the general arrangement is adequately shown by the illustration in the manuscript reproduced as Fig. 11.[36] The olives shown here without any containing vessel were really placed in a lead bag or vessel.

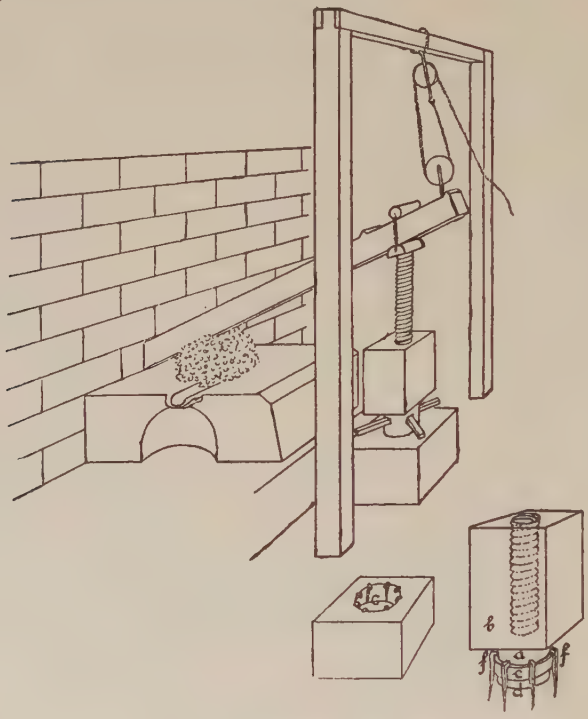


FIG. 11.—Beam press with screw.

Besides these large presses, a smaller appliance worked entirely by screws came into use towards the close of the pre-Christian era. Hero describes it as an olive press that is not only more convenient to handle but actually more powerful. The general character of the apparatus is sufficiently clear in the drawing reproduced in Fig. 12.[37] A press with one screw is also described, essentially similar in most aspects to the simple book presses of today.[38] The

[36] SCHMIDT, "*Heronis opera*," Vol. II, 1, p. 230, Fig. 57; for this type of press about 1169 A.D. see, HERRAD, Abbess of Landsberg, "*Hortus Deliciarum*," plate 61.

[37] SCHMIDT, "*Heronis opera*," Vol. II, 1, p. 242, Fig. 59. Carra de Vaux gives a different version of this figure.

[38] SCHMIDT, "*Heronis opera*," Vol. II, 1, Book III, Sec. 21.

excavations at Pompeii have revealed wall paintings of presses with two screws applied to pressing cloth.[39] The process of mak-

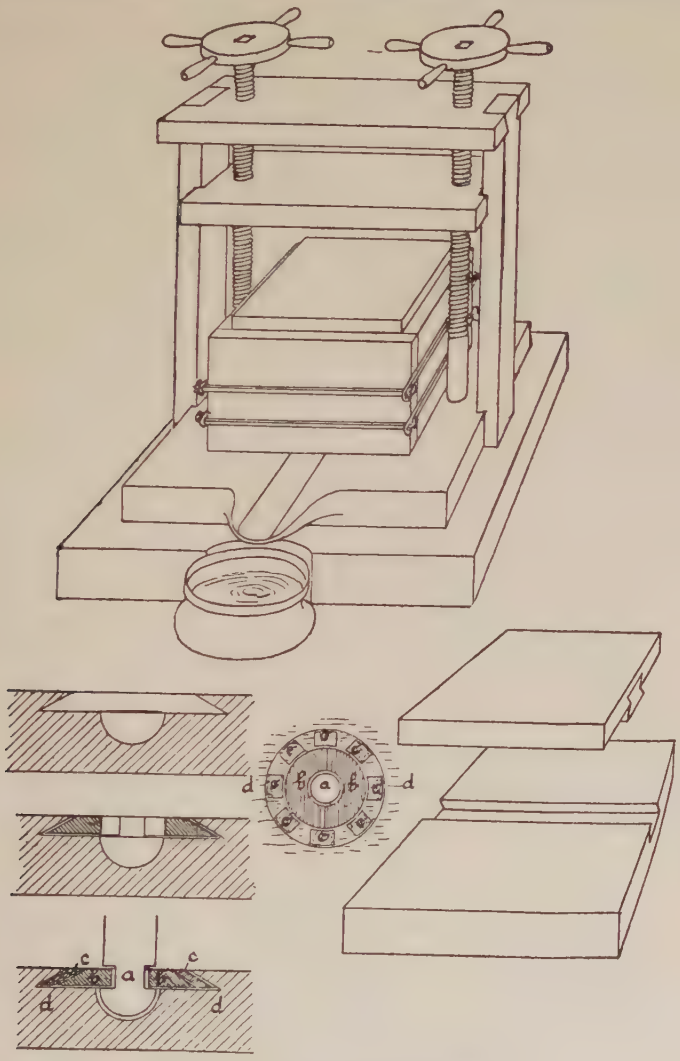


FIG. 12.—Small screw press.

ing the screws out of wood is also described by text and figures. While it is not possible to date any of these inventions with even approximate accuracy, and though the names of all the inventors

[39] BLUMNER, Vol. I., p. 188, Fig. 73; BECK, G. D. E. Vol. I., p. 575.

are hopelessly lost, it must be clear that development was active throughout the last two centuries of the pre-Christian era. Furthermore, the major accomplishments described by Hero must have been relatively recent in his time.

The application of the screw to the raising of water was relatively old. Although Archimedes is frequently credited with the invention of the water screw on the strength of statements by Diodorus Siculus and Atheneus, there are grounds for supposing that such a device was known in Egypt before the time of Archimedes. His achievement would then consist in technical improvements in construction and in the diffusion of the device outside of Egypt. The primary features of the simpler form of the water screw are shown in Fig. 13[40] which is based upon the text of Vitruvius.

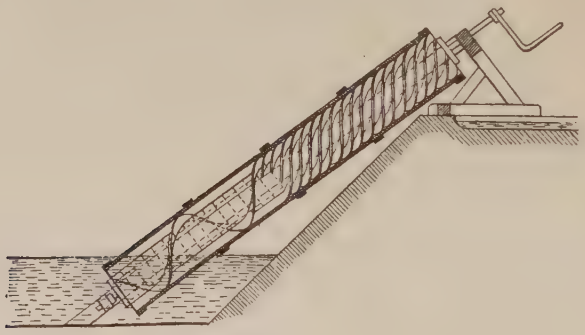


FIG. 13.—The water screw.

This device was used to clear the holds of ships, to keep mines free from water, and to raise water for purposes of irrigation. It was used in Europe during the Middle Ages and in the early modern period, and was used for centuries in the Far East. The particular convenience of the apparatus is due to its adaptability to raising water in restricted spaces.

The wheel was applied at an early date to the task of raising water to great heights; there are two forms, the *noria* or Egyptian wheel and the chain of pots which is frequently, though inexcusably, confused with the noria. The noria consists of a large wheel having a series of containers fastened inside of the rim. In the less developed forms these containers are rigid. They are partially filled with water as they pass through the stream and they begin to discharge before they have reached the top, so that the water cannot be raised to the full height of the diameter of the wheel.

[40] BECK, G. M. B., p. 50, Fig. 57.

A modification, introduced before the Christian era, is shown in Fig. 14.[41] The buckets are attached to the wheel by pins upon which they swing freely. At the top, the bottom of the bucket strikes against a bar which empties it into the gutter leading to the reservoir. The figure implies that the wheel was turned by the current of the stream. The large noria were commonly turned by treadmills or windlasses. Wheels were built 30 and 40 feet in diameter, and, though they were rarely driven by water power, they could be operated as undershot wheels in swift rivers and it is thus likely that they represent the earliest application of water power.

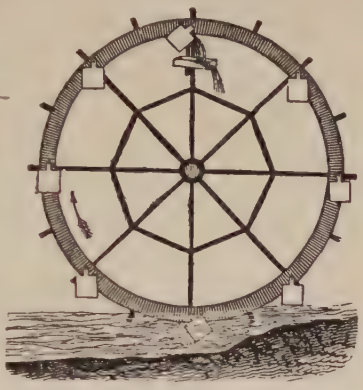


FIG. 14.—Developed Noria.

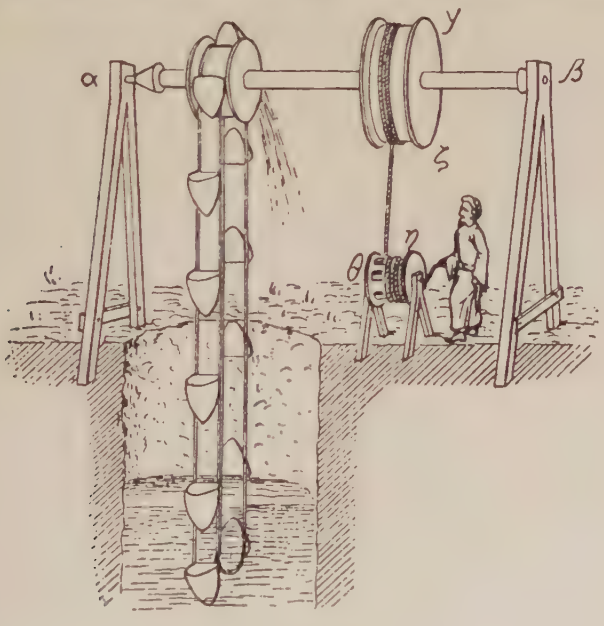


FIG. 15.—The chain of pots.

When water was to be raised to even greater heights, or when relatively deep wells were involved, the principle of the noria was

[41] EWBANK, p. 115, Fig. 51. The text of Vitruvius describes a noria of this type: "Vitruvius," ed. Choisy, Vol. III, p. 195.

modified by attaching the buckets to a belt which passed over drums at the top and bottom of the lift. Such an apparatus had no specific limits beyond the amount of power disposable. For wells and short lifts an arrangement could be made to be worked by a single man. Philo of Byzantium (third or second century B.C.) shows two devices of this type for use in wells of 15 cubits (about 22 feet).[42] The piece of apparatus commonly used is shown in Fig. 15.[43] The chain of pots is shown, too, as employed for raising water to a cistern in a house or for use in a fountain. The apparatus is to be installed at such a level below the stream that the force of the water will drive the whole mechanism. Whether this was largely an idea of the writer or a record of things actually accomplished is not wholly clear from the text, though there is evidence of concrete experience in the remarks about the proportion between the force of the current and the number of buckets that might be lifted. Here again there is an indication of an application of water power, though commonly such devices were turned by windlasses or treadmills. Later, animal power was extensively used in connection with windlasses, but this required some gearing and there is no reliable evidence of any extended application of animal power prior to the Christian era.

III

The missile weapons of antiquity and the Middle Ages were developments of the bow and the sling, and of the two lines of growth the former is the more significant from a technological standpoint. Attempts to strengthen the bow made it essential to provide mechanism for drawing it and holding it in readiness for release. Increased strength required not merely the use of heavier wood for the bow, but additional flection elements. It was necessary to separate the bow into two arms and most of the flectional power was transferred from the heavy wooden arms to the attachment in the head of the machine. A large crossbow of late antiquity is shown in Fig. 16.[44] The elastic elements in this instrument are thongs of heavy leather or ropes which are held in perforated iron rings. These rings could be wound up in order to tighten the bands in time of action and to make it possible to release the pressure at other times. The drawing shows clearly the ratchet

[42] CARRA DE VAUX, "*Les pneumatiques de Philon*," pp. 224, 225.
[43] CARRA DE VAUX, "*Les pneumatiques de Philon*," p. 224, Fig. 10.
[44] DIELS and SCHRAMM, "Heron's *Belopoiika*," p. 24.

and cam attachments controlling the string as the bow is drawn back by the small windlass at the rear. The arms of the windlass are not shown, being presumably detachable. The drawing is based upon the illustrations accompanying the text of the treatise

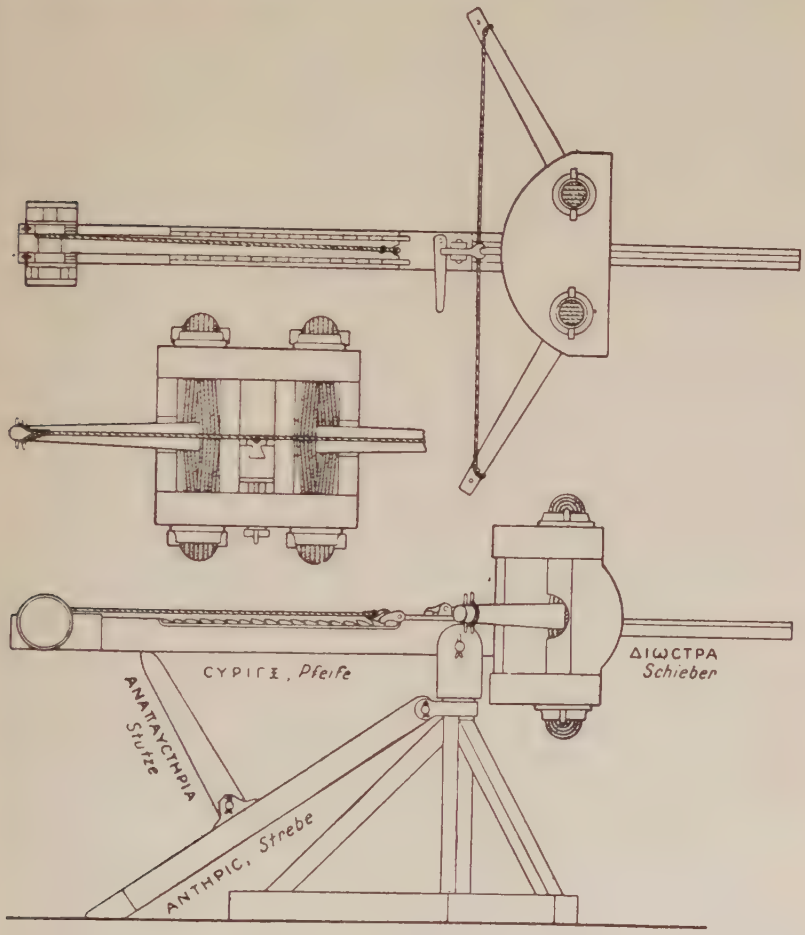


FIG. 16.—Cross bow of Hero.

of Hero of Alexandria, but the detail of the figure is wholly modern, so that the quality of the ratchet work cannot be considered an exact representation of ancient workmanship. This type of machine was designed to shoot a long arrow. Other types were made for balls and short arrows.

Modern reconstructions of these machines, built by Lieutenant Schramm, had maximum ranges of 325 yards for the smaller types with probable ranges of 400 yards or more for the larger types. Stone balls ranging in size from 3 to 10 pounds have been discovered in the excavations at Numantia, in Spain, probably relics of the siege by Scipio the Younger in 133 B.C. These were thrown in part by catapults, and in part by weapons of the general design shown above. The range of the small catapults as reconstructed was about 325 yards.[45]

These various weapons are now believed to have been invented about 400 B.C. at Syracuse in the time of Dionysius the Elder. Signal improvements were made by Ctesibius and Philo of Byzantium in the second century B.C. and some innovations were then suggested that proved in the end to be impractical. The instruments were sensitive to the weather, because rain or even dampness destroyed much of the power of the thongs or rope used as a flectional element. Philo suggested the use of compressed air chambers and of bronze springs, as a source of power. The air chambers were set behind the ends of the arms of the bow with the idea that the air in the chamber would be sufficiently compressed when the bow was drawn to yield significant power. Lieutenant Schramm attempted to construct the machine as described in Philo's text, and after experiment, reached the conclusion that the machine would be of no practical use unless the air in the compression chamber were brought to a relatively high pressure by means of a force pump. He assumes, therefore, that Philo never actually built the machine as described. If this is the case, the description in the text furnishes an instance of an invention conceived in the imagination and worked out in sufficient detail to be executed as a drawing. Two different versions of the detail of the compression chamber appear in the reconstructions by Diels and Schramm and in a figure cited by Feldhaus.[46]

The attempt to apply leaf springs of bronze was perhaps a happier idea, and the apparatus as described seems not impracticable, but there is no evidence that springs of either bronze or steel came into general use and the absence of any reference to such flectional elements in Vitruvius and Hero furnishes a strong presumption against their use. The passage in Philo is the first clear

[45] DIELS, "*Antike technik*," pp. 93, 99, 103.

[46] DIELS and SCHRAMM, Heron's *Belopoiika*, Tafel 6., Feldhaus, Technik der Vorzeit, p. 403.

indication of any realization of the possible significance of the elasticity of metals, and it must have been a new idea as Philo devotes a whole paragraph to the reality of elasticity in metals. He cites particularly the mode of testing Celtic and Spanish swords by bending them, and calls attention to the exact and immediate resumption of their former shape. Until that time there is no record of the use of any form of metal spring except in certain types of pins approximating the form of the modern safety pin.[47] Feldhaus gives no record of the use of leaf springs before the later sixteenth century; nor any record of spiral springs in locks or other devices before the fifteenth century. Diels believes that Philo's attempt failed because of technical difficulties in the use of bronze. The incident furnishes almost decisive evidence against the likelihood of any extended application of springs in mechanical devices during antiquity. The positive contribution of military technology was thus confined to the cams, ratchets, and other devices for arresting and releasing motion. Though such devices might well have been useful on the heavy beam press, they do not appear in any of the drawings or descriptions, so that the applications seem to have been confined to military apparatus.

The treatises on pneumatics of Philo and of Hero are occupied primarily with devices based upon the siphon. There are tantalus cups, sprinklers, cups with a constant level, altar figures pouring libations, singing birds, and various set pieces of figures. Of the more elaborate of the set pieces, one shows Hercules shooting the dragon that guarded the golden apples—and the other shows a horse or an ox that drinks after its head has been cut off. These pieces present some interesting details, but nothing of outstanding importance. Curiously enough, there is little direct evidence of any general use of a vacuum pump, although Ewbank presumes that use was made of the simple form still in use as a bilge pump in small boats.[48] There is no ground for doubting this conclusion, but neither is there any clear evidence to confirm the presumption.

The force pump appears, however, both in its simplest form as the syringe and as a machine of moderate compass that ultimately came into fairly general use as a domestic pump and as a fire engine. The invention of the force pump is ascribed to Ctesibius, but owing to the loss of his treatises the earliest description is

[47] Hero used a small spring of horn in the key action of his organ.

[48] EWBANK, pp. 214–215. The figures, however, are based on sixteenth-century materials.

afforded by the treatise of Philo. The text is accompanied by the drawing reproduced in Fig. 17.[49] The apparatus shows little economy or elegance in design, but all the essential principles appear. Except for the presence of two pipes conducting the water from the pump cylinders to the reservoir, the description would not be inconsistent with the remains of pump heads that have been discovered in various Roman ruins in Europe and the description given by Vitruvius. Water flows into the partial vacuum created

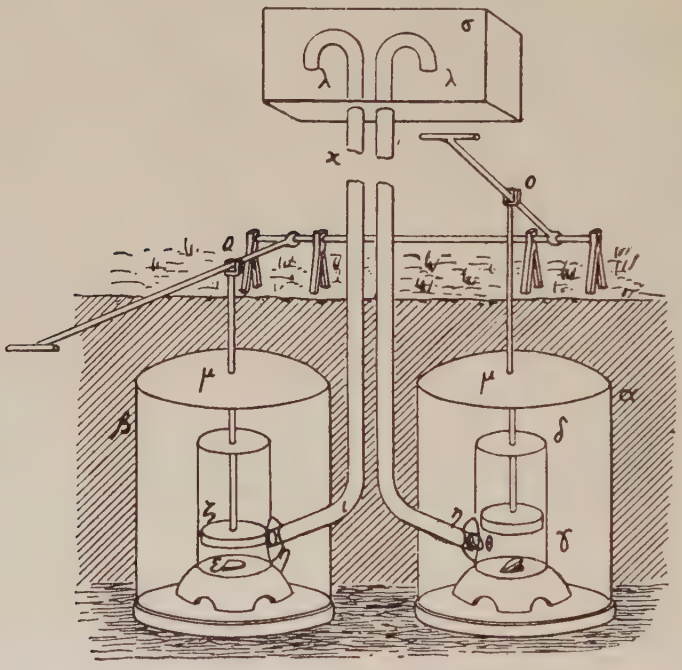


Fig. 17.—Philo's force pump.

by the ascent of the piston in the cylinder, and then on the down stroke, the valves reversing, the water is forced up the pipe into the reservoir. In the text, the pipes are stated to be 10 cubits (15 feet) in length. The description of the pump in Hero's "Pneumatics" (Book I, Chap. 28) states explicitly that it was used as a fire extinguisher, and the text of Vitruvius seems to have the same application in view. Neither of these texts, however, indicates the mounting of the pump for prompt conveyance to the scene of

[49] Carra de Vaux, "*Les pneumatiques de Philon*," p. 217.

the fire. Archæological discoveries show that the same principle was applied to the raising of water from wells as suggested in Philo's text. Remains of two small pumps were found at Bolsena, Italy, representing the general features of the text of Vitruvius. Other remains of a much more advanced type have been found at Silchester, at Metz, and at Ste. Germain en Laye. These remains are all of the same general type. The finds consist of a heavy block of wood with portions of lead pipe in varying states of preservation. At Silchester, this block was found at the bottom of a well about 9 feet deep. It is;

FIG. 18.—Remains of a pump found at Silchester.

"... seemingly oak, (Fig. 18)[50] 22½ inches long, and now roughly wedge shaped, but originally its sides seem to have been parallel. The broader end, which was the base, measures 13 by 9 inches. Towards the top the wood has perished somewhat from decay. The block is pierced throughout its length by two large cylindrical holes, which, when we found it, contained each a section of stout lead piping. The pipes or cylinders are a little over 22 inches in length, and have been formed from pieces of sheet lead 3/16 inch thick, which have been bent around a mandril and the joint filled up with melted lead. Their internal diameter is

[50] ST. JOHN HOPE, W. H. and GEO. FOX, Excavations on the site of the Roman city of Silchester: "*Archeologia*," Vol. 55, 1, p. 232.

exactly 3 inches . . . Besides the two cylindrical holes that contained the pipes, one face of the block is traversed by a chase from which a totally different series of pipes has been removed. Commencing at the top there was a pipe about 8 inches long, and apparently 2½ inches or so in diameter, with a trumpet-shaped mouth. It opened at the bottom into a flattened bell-shaped chamber about 7 inches long and 5 inches wide from which descended two parallel lengths of piping about 2 inches in diameter and at least 7 inches long. Just above the base of the block there is a passage, or rather perforation, from each of the channels for the small pipes into the larger cylindrical holes, showing that originally the lesser pipes were connected with the others by short branches. This arrangement was afterwards altered, for the existing pipes, which are practically perfect, show no traces of the attachment of such branches . . . There can be little doubt that in its original state it contained a force pump identical in character with that described by Vitruvius as the Ctesibica Machina."[51]

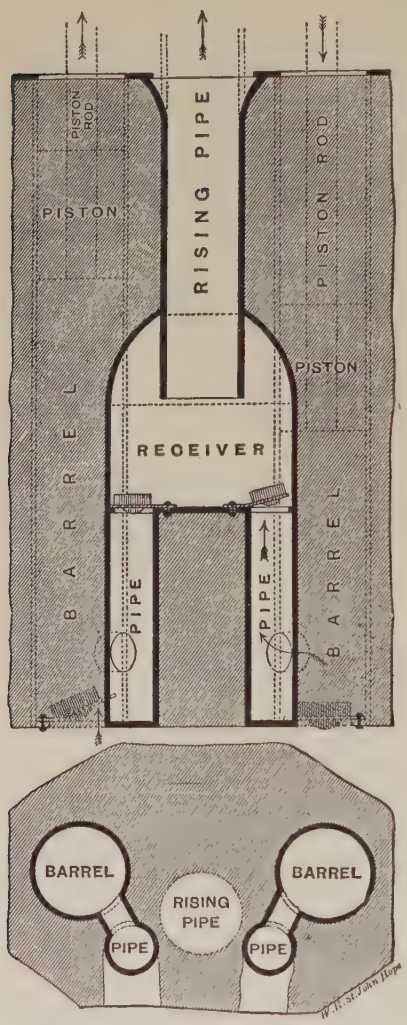


Fig. 19.—Reconstruction of the pump found at Silchester.

The reconstruction of the pump shown in Fig. 19[52] presents a striking contrast with the cumbersome apparatus sketched in

[51] "*Archeologia*," Vol. 55, 1, pp. 232–233.
[52] "*Archeologia*," Vol. 55, 1, p. 234.

Philo's text. The apparatus is compact, relatively inexpensive in respect of materials, and well conceived in its design. Apparently, this was one of the established forms of the domestic pump.

In principle, it should have been possible to apply these pumps to the development of a high-pressure system for the distribution of water, but there was no means of working any but small hand pumps. Ewbank publishes a drawing of this force pump in which it is driven by an undershot wheel,[53] but there is no warrant for such a conception of the text of Vitruvius. In fact, the system of water distribution in antiquity was based exclusively on gravity. The aqueducts delivered water directly into various "water-castles" containing reservoirs, the highest of which were practically level with the aqueducts. The water was led by pipes to the public and private fountains, through which it flowed continuously.[54]

The organ has a long history in antiquity, beginning with a small apparatus that is hardly more than a bagpipe. Its real career begins, however, with the appearance of a device blown by one or two leather bellows. In antiquity, this form soon gave place to the so-called "water organ," in which the wind was furnished by one or two compression cylinders; the pressure was kept constant by the addition of a central wind chamber in which water served as a stabilizing pressure medium. The invention of this type of organ is commonly ascribed to Ctesibius, but some doubts of identity are raised by a passage in Atheneus which implies the existence of a Ctesibius distinct from the engineer and inventor. The problem admits of no wholly satisfactory solution, but the invention of this instrument is, in any event, placed at least as early as the second century B.C. No descriptions are available earlier than the treatises of Vitruvius and Hero, though some vague representations in archæological fragments are available from the pre-Christian period. It seems clear that both types of organ were developing side by side, though the water organ receives most attention in the treatises. The description in Hero's "Pneumatics" is the most complete, and is happily provided with adequate figures.

The general arrangement of the apparatus is shown in Fig. 20;[55] but the drawing unfortunately fails to show the valve at the junc-

[53] EWBANK, p. 267, Fig. 121.

[54] MERCKEL, K, "*Ingenieur technik im Alterthum*," pp. 544–551.

[55] SCHMIDT, "*Heronis opera*," Vol. I, p. 194, Fig. 43; p. 195, Fig. 43*a*, Fig. 43*b*.

tion of the pipe leading from the compression cylinder to the wind chamber. The containing vessel $\alpha\beta\gamma\delta$ is explicitly stated to be bronze; and Vitruvius makes it clear that the cylinder was also of bronze. When the piston is drawn down, air enters through the valve at ω (Fig. 21). With the return stroke this valve is closed and the air is forced into the dome-shaped air chamber at the bot-

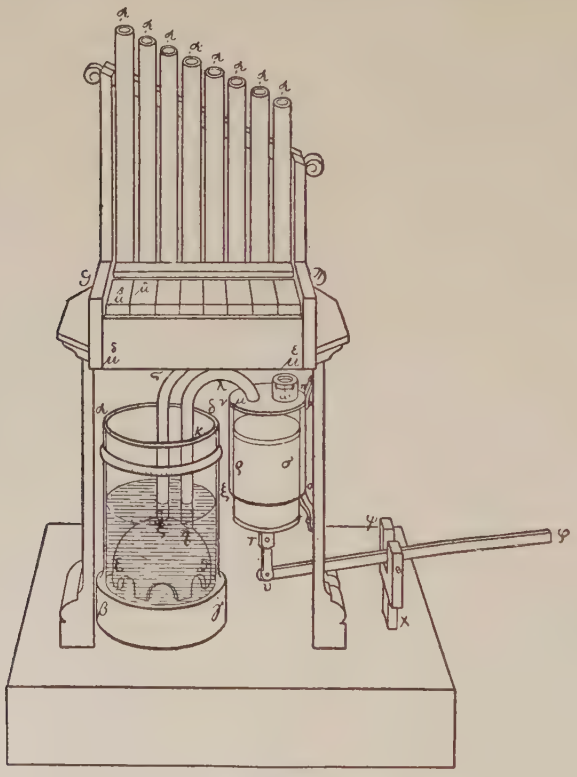


FIG. 20.—The water organ: general assembly.

tom of the large container $\alpha\beta\gamma\delta$. The air is retained under the dome at a measurably constant pressure, by the water in the container. When air flows into the organ, water pushes up under the dome, keeping the remaining air under pressure. As air flows into the dome from the cylinder the water is expelled. Ewbank presumes that this type of organ was superior to a bellows-blown organ because he believes that no bellows then made could have produced as high a pressure or as steady a flow of air, but the small

scale on which the water organ was built does not lend much force to such a presumption. The use of bellows was thoroughly understood and they were used in coupled pairs as well as singly, so that one wonders what their relative efficiency might have been. For the time at least the water-organ attracted the most attention.

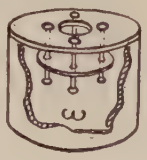


FIG. 21.—Valve action of the water organ.

The action of the keys is shown in Fig. 22. In the position shown, no air can enter the organ pipe, but if the key is depressed the small block is pushed back until a hole connects the air passage with the organ pipe. When the key is released, it is returned to position by the string attached to the piece of bent horn at the right.

A modification of the organ for less serious purposes is shown in Fig. 23.[56] This organ sounds whenever the wind blows, and as it has no keys nor any central wind chamber it is fairly evident that it was not used for any serious musical purpose. The interest of the apparatus lies in the fact that this is the only explicit reference

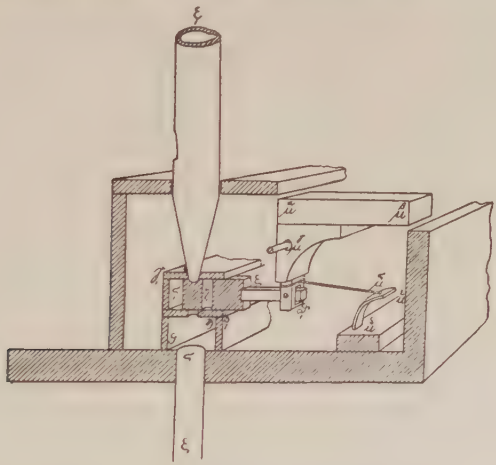


FIG. 22.—Key action of the water organ.

to the use of a "windmill" in antiquity. The illustrations for this chapter of Hero's text present a wide range in form, from presentations that embody every feature of a self-adjusting windmill to the rather crude apparatus shown in this drawing based upon the illustrations of the basic manuscript. As the manuscript

[56] SCHMIDT, "*Heronis opera*," Vol. I, p. 205.

probably dates from the twelfth or thirteenth century it is not likely that the copyist would have been significantly prejudiced by too much knowledge of the windmill as known to us, and if the drawings were present in the original text there is reasonable ground to presume that these drawings are at least measurably related to the originals. The terms used in the Greek text, too, can be defensibly translated without implying common knowledge of windmills, for the word "anemurion" may be taken to mean

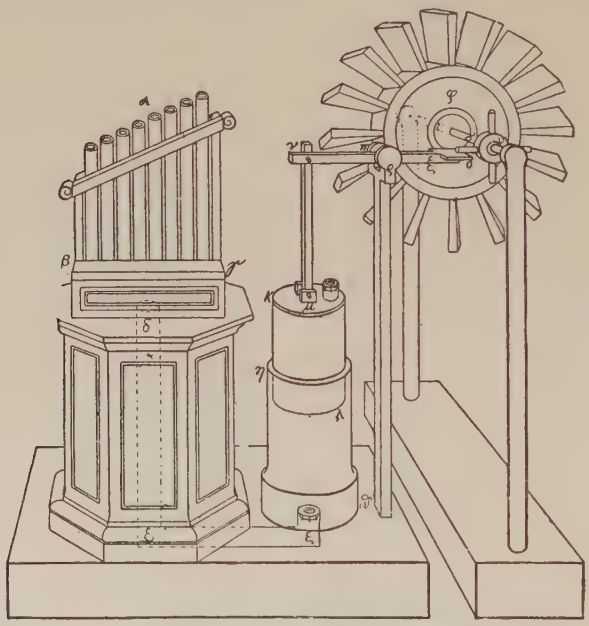


FIG. 23.—Organ with wind wheel.

something that rotates in the wind on a pivot. To translate it as the "sail of a windmill" is in this instance a question-begging translation.

The trip-hammer motion shown is also of interest. The piston is supposed to descend of its own weight, to be raised by the trip mechanism attached to the axle of the wind wheel. This apparatus is perhaps one of the most striking demonstrations of the distinctions between the production of motion and the production of power, for this little device embodies two notable arrangements that ultimately appear in heavy-duty machinery. The trip hammer also appears in one of the devices of the puppet theater, in an

arrangement to make one of the figures hammer at an anvil.[57] The date of the appearance of the windmill as a source of power is wholly uncertain but it could hardly have appeared until several centuries later than Hero's treatise. The trip hammer was not developed until the fifteenth century. The invention of apparatus to produce motion thus precedes mechanism to produce power by a long interval. Until significant sources of power could be effectively controlled and utilized, these devices for the production of motion were scarcely more than models, useful for amusement or in instruments of precision.

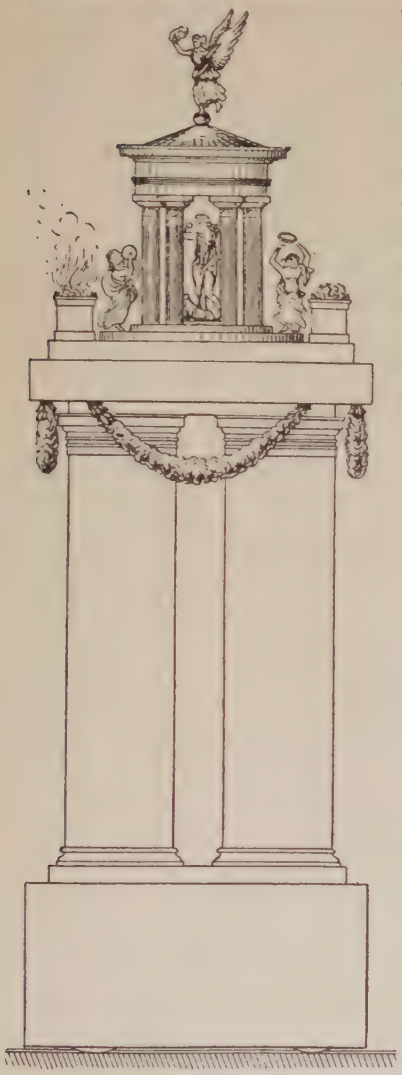


Fig. 24.—Puppet theatre: temple of Bacchus.

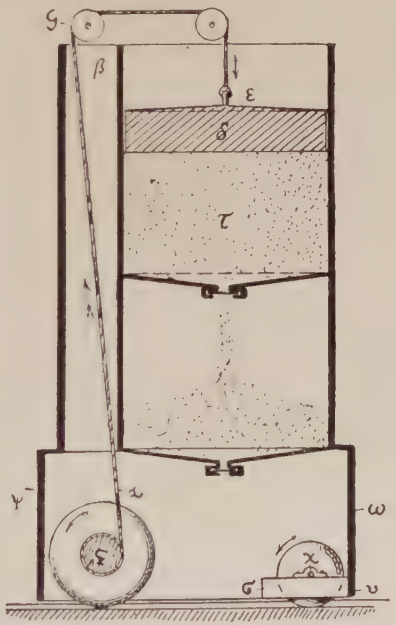


Fig. 25.—Puppet theatre: driving mechanism.

[57] Schmidt, "*Heronis opera*," Vol. I, p. 425, Fig. 103*a*.

The treatise on the puppet theater contains descriptions of weight-driven mechanisms that are especially interesting in connection with the development of the weight-driven clock. The power for nearly all this kind of mechanism was furnished by falling weights. The treatise describes in great detail the building of two pieces of apparatus, together with some incidentals. One type of performance was given with a piece of apparatus that ran up and down a track under its own power, while the puppets carried out a series of actions. The general aspect of the device is shown in Fig. 24.[58] A small temple is carried on a platform sustained by two substantial pillars. The altar fire is lighted. Five or six dancing girls perform on a circular platform that surrounds the temple. Within stands a figure of Bacchus, that turns about and pours a libation. On top is a figure of a winged victory that also makes certain movements. The driving mechanism of the apparatus as a whole is shown in Fig. 25.[59] There are three wheels, the driving axle with two wheels, and a following wheel. The source of power is a lead weight, δ suspended in a cylinder or box filled with millet or mustard seed. The driving cord passes from the weight over two pulleys to the driving axle, on which it is wound in such a fashion as to produce motion in both directions. The first phase of the winding carries the carriage out, when the motion is reversed and the carriage returns to its original position. The full description of the apparatus is too complex to be given in this connection. For the present purpose, it is enough to note the use of the falling weight and the simplicity of the means of application and control.

IV

There is a large group of tools and mechanisms which may be described as instruments of precision: instruments for mensuration and calibration; instruments for optical observation of all classes; instruments for the measurement of time; mechanisms and processes for the exact production or reproduction of objects. Many of these instruments are only indirectly concerned with industrial production in the narrower sense, but they play an important part in the history of mechanical appliances and in the development of technology. Any complete survey of the instruments of the ancients would be out of place, but a number of achievements towards the close of the pre-Christian period were of the greatest

[58] SCHMIDT, "*Heronis opera*," Vol. I, p. 351, Fig. 82.
[59] SCHMIDT, "*Heronis opera*," Vol. I, p. 361, Fig. 86.

importance. The development of the water clocks, of the cyclometer or hodometer, and the perfection of surveying instruments furnish significant evidence of the technical proficiency of the period.

The water clocks present the most difficult critical problem, because we have no complete contemporary descriptions. Hero's treatise is unfortunately lost, except for a small fragment, and the text of Vitruvius is so incomplete in its details that no wholly adequate drawings can be prepared. If the text is followed literally the apparatus is oversimplified; if details are filled in the result is likely to express the conditions contemporary to the draughtsmen. This danger is serious. The water clock remained in use until the seventeenth century, and as a result the renaissance editors of Vitruvius supplied the text with figures which were profoundly influenced by constructions then current. These plates have been widely copied and are to be found in many of the technical treatises on horology, with or without indication of the precise source of information. The presence of a water wheel in these figures is hardly warranted by anything in the text of Vitruvius, and there is little justification for the kind of gearing that is shown, though some of it would not be beyond the compass of the age that could construct the cyclometer as then known.

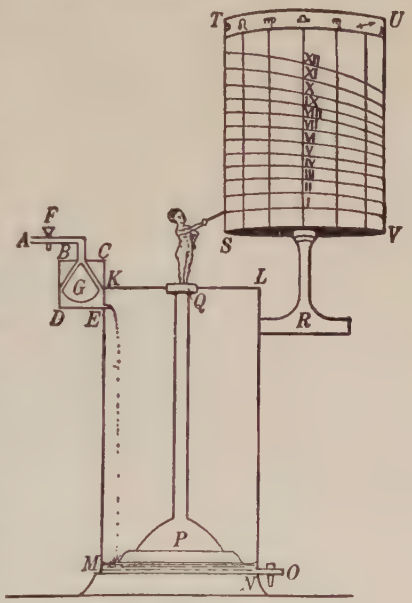


Fig. 26.—The water clock.

The best modern critical achievements are embodied in the drawing by Diels reproduced in Fig. 26.[60] Water is allowed to fall into the vessel *KLMO* through the small opening at *E*. By appropriate regulation, the rate of flow can be made uniform, so that the increase in the volume of water collected in the basin affords a sensibly accurate measure of time. The hours may be

[60] Diels, "*Antike technik*," p. 206.

indicated in various ways. The simplest means is shown in the figure. A float with a rod and indicator can be made to register against a graduated scale. In the illustration, the scale is a cylinder with hours of varying length marked off. For general purposes, the period of daylight was divided into 12 hours regardless of the seasons so that the variations in the length of the period of daylight produced variations in the length of the hour. Perrault's plates show an arrangement of gears driven by a water wheel moved by the water drawn from the basin *KLMO* by a siphon whenever the level in the basin passed the band of the siphon. We have no certain evidence that such a device was actually used in antiquity, though it was in use in the sixteenth century. The cylindrical dial had to be set periodically for the season. Vitruvius says explicitly, however, that other motions were produced.

"Other rods and other gears and dials driven by the single source of motion produce by rotation various effects and varieties of motion. Small figures are moved, posts turn, pebbles or eggs are dropped into a gong, trumpets sound, and other accessory motions are produced."[61]

There is thus no warrant for supposing that the clocks were built with narrow conformity to a single type. There were varying degrees of complexity and doubtless considerable variations in the character of the supplementary mechanism. The figure must thus be taken as a presentation of the bare essentials of the mechanism without any of the accessories that were in use.

The special significance of the reconstruction by Diels is the device for regulating the flow of water from the primary reservoir. This is shown in the figure as a small tank *BCDE* served by a pipe ending in a conical cavity. The float *G* is made exactly to fit this cavity. If the flow of water through the tube *A*, from a reservoir not shown, were too rapid proportionately to the flow at *E*, the water in the reservoir *BCDE* would rise until at last the float would be raised into the opening of the pipe, completely shutting off the water until the loss from the reservoir *BCDE* allowed the float to sink and admit more water. This device was extensively used by the Arabs in elaborate forms, and it seems to have been used in some form by the beginning of the Christian era.

Vitruvius describes also another type of water clock, in which the recording dial is a circular plate (Fig. 27)[62] which revolves

[61] "Vitruvius," ed. Choisy, Vol. III, p. 158.

[62] Diels, "*Antike tecbnik*," Plate XVIII.

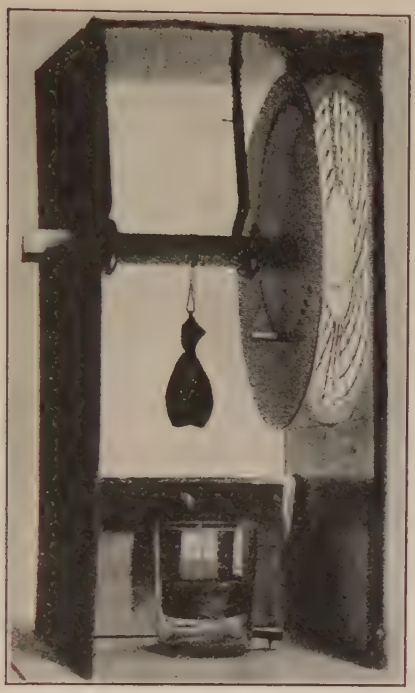


FIG. 27a.—Astronomical water clock.

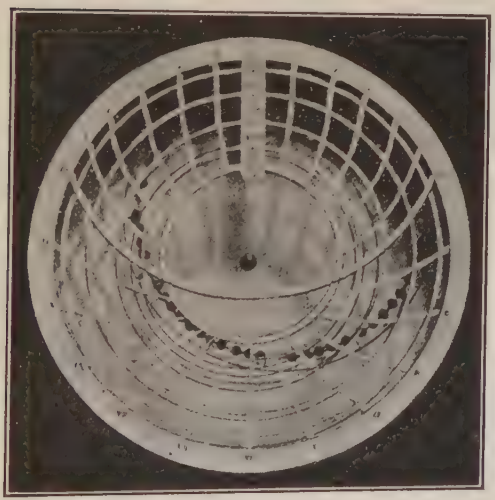


FIG. 27b.—Astronomical water clock.

behind a dial cut in a special pattern to represent the movement of the sun throughout the year. When the peg is properly located in the solid dial its movement will indicate the proper hours when read from the outer dial. The reconstruction of these dials is based upon the text of Vitruvius and the large fragment of a bronze dial found at Salzburg at the beginning of the present century. The two sources, when combined, leave little doubt as to the general character of the apparatus. In this clock the driving mechanism is somewhat altered. The axle of the mobile dial is turned by a light chain connecting a bag of sand that is carefully counterpoised with a float (here shown in a glass container). This is the general type of weight-driven mechanism shown in the mobile altar of Hero's puppet theater for the display of the libation to Bacchus. It is the earliest form of the application of weights to a timepiece, indicating explicitly the simplicity of the transition to a use of a falling weight as a source of power. Of the accuracy of the water clocks we have no sufficient knowledge. The chief source of constructional trouble was at the outlet *E*; any obstruction there would be serious. The orifice was thus made of gold or some precious stone. At the best, the device must have been significantly accurate, for Galileo's experiments with falling bodies were conducted with a special form of water clock in which the water was measured by weight. The practical difficulty lay in the individuality of each instrument, and in the need of constant attention to the reservoirs of water and to the condition of the conduits and orifices. There is no information on the average performance of the water clock.

Cyclometers are described both by Vitruvius and by Hero in essentially similar forms. The device is historically important because it is apparently the earliest general application of a chain of toothed wheels and pinions. Some toothed wheels appear in the devices described in Hero's "Pneumatics," and there is a diagram in the "Mechanics" which shows a train of wheels to be used for the moving of a heavy weight. It is generally held, however, that no such train of toothed wheels was actually applied to the transmission of power. The flour mill described by Vitruvius had only one pair of toothed elements and that is the only well-authenticated case of the application of a toothed wheel to the transmission of power. The idea appears frequently in the transmission of motion in the minute apparatus, but nowhere on the scale shown in the cyclometer (hodometer). Five pairs of elements

are shown in the drawing (Fig. 28)[63] and the text implies the use of several pairs, though the number is not specified. Apparently, the device was expected to be attached to a wagon, and it was recommended that the registering capacity of the device should not greatly exceed the average day's journey. The first wheel is specifically said to be of brass, nothing further appearing about materials of construction. Although the device is simple a vast series of mechanisms were ultimately to be produced by the application of the mechanical arrangements involved. But in Hero's time scarcely any progress had been made beyond the elementary concepts embodied in this cyclometer.

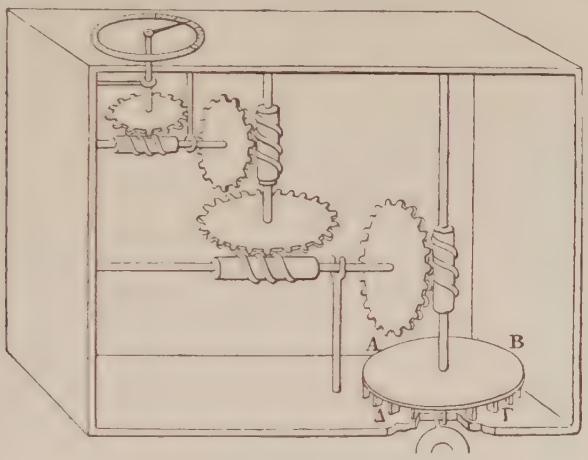


FIG. 28.—Hodometer (cyclometer).

The first early instruments of precision for observation were largely designed to meet the needs of astronomers. The basic forms were the cross-staff and the astrolabe. The invention of the cross-staff is ascribed frequently to Archimedes (287–212 B.C.), but Gunther thinks that it may have been known to Aristotle (384–322); further improvements were made by Hipparchus (flourished 161–126 B.C.). The primary instruments, notably the astrolabes and quadrants, were developed by Hipparchus and perfected by his followers. By the time of Claudius Ptolemy many of the instruments had assumed stable forms which they retained until the development of optical lenses in the sixteenth century. Despite additions and improvements by the Arabs and Europeans

[63] SCHMIDT, "*Heronis opera*," Vol. III, p. 295, Fig. 114.

the basic observations of the new astronomy were made with the old instruments. Copernicus used precisely the same instruments as Ptolemy; the achievement was speculative rather than observational.[64]

One of these instruments, the dioptra, was developed by Hero into a satisfactory instrument for surveying. The task of measuring small angles with accuracy required considerable delicacy of adjustment. An instrument of this name is associated with the name of Euclid in the fourth century, but its scope must have been limited. Hipparchus made improvements, but with reference to astronomical use. Hero developed the instrument and restated the theory of surveying. Egyptian and early Greek surveying had been based upon the use of the "star" or "groma," which has been reconstructed as shown in Fig. 29.[65] Practical difficulties were experienced in bringing the "star" into a stable position, because the weights kept moving for an appreciable period. Wind would move the strings and weights sufficiently to interfere with observation, and in Hero's time much effort was being made to find a remedy. The weights were at times enclosed in tubes, but then it was difficult to make the apparatus level and if it were not made level serious errors were encountered.

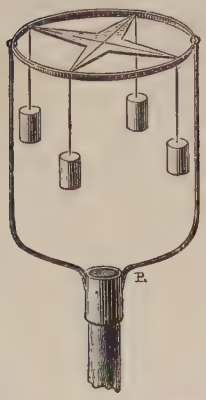


FIG. 29.—The groma (surveying star).

The accuracy of the levels of ancient aqueducts has been studied by modern students, with results that indicate substantial elements of error. In six aqueducts of Vitruvius' time the actual fall per kilometer was less than the proportion of 1 to 200 which was regarded as the minimum allowable. The aqueduct at Sens reveals the lowest inclination in Roman practice; 0.5 meter per kilometer or 1 to 2,000. Furthermore, in a section of 5,990 meters studied by Belgrand there were inexplicable variations ranging between 0.01 and 2.47 meters per kilometer. Under the circumstances, it seems that the elements of error must have been considerable. In general, the aqueducts were built with greater inclination than was theoretically necessary in order to offset possible errors, and, in consequence, the water was brought into

[64] GUNTHER, "Early Science at Oxford," Vol. II, pp. 9–19.
[65] DE ROCHAS, "*Origines de la Science*," p. 237, Fig. 96.

the cities at lower levels than was really necessary, much to the injury of the service. Much of this work, however, was done by the chorobate, a table about 20 feet long equipped with plumb

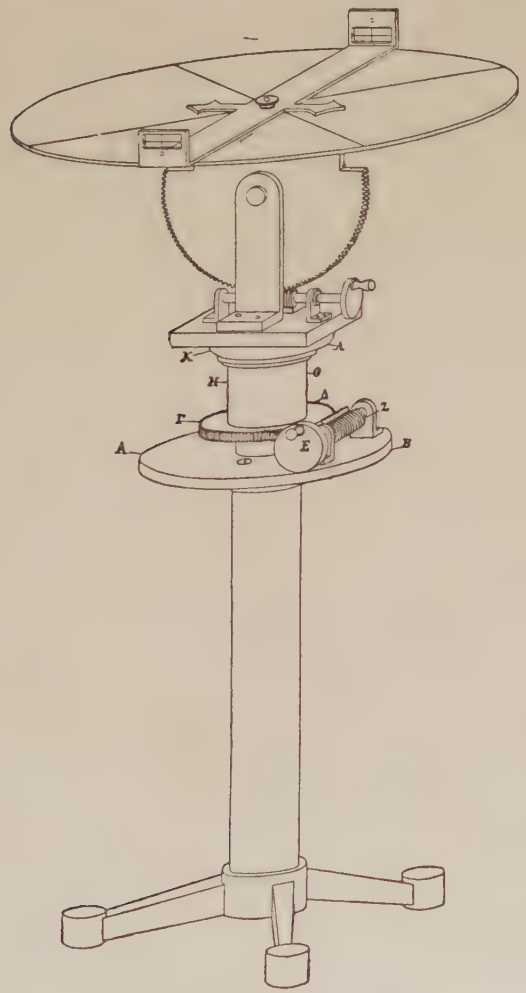


Fig. 30.—The dioptra.

bobs and a large water level. It must be remembered, too, that in driving the tunnels so frequently used for aqueducts, sufficient accuracy could be achieved to make it practicable to work simultaneously from both ends. Two well-known achievements of this type are the 533-meter tunnel driven for the service of Jerusalem

early in the seventh century B.C., and the tunnel at Samos late in the sixth century.[66] It is not clear that the improvements in instruments down to the time of Frontinus exerted any demonstrable influence on the accuracy of this kind of work.

On the whole, Hero's work on the dioptra seems to have been substantial and new; it may well have been one of the most original of his achievements and in that case it lies somewhat beyond the time limits of the present chapter. For various reasons, however, it may best be discussed at this point. Hero's improvement consisted in mounting a water level in a stand conveniently arranged for observation. The general arrangement of the apparatus is shown in Fig. 30.[67] Some plates show a plumb line at one side of the shaft of the stand, but apparently the leveling of the apparatus could be tested by the position of the water in the tubes of the water level rising in each of the sights of observing frame. The mode of adjusting the apparatus to inequalities in the ground does not appear. The screw *EZ* could be employed to face the apparatus in a given direction. The text makes it clear that the screw above the capital *AK* was used to measure vertical angles, though no graduations are indicated on the toothed semicircle engaging the screw. In conjunction with this instrument was used a staff with a moveable sighting disk similar in all essentials to the modern surveyor's staff. The manner of using the instrument is described in great detail with complete diagrams of various problems in surveying and measurement.

V

A number of important appliances are not mentioned in the treatises at all; some because they were commonplace, others because they had hardly achieved the dignity of being machines. Of these items the most important at the time was the mechanism for grinding. In early society, grinding was commonly done in mortars or on slightly hollowed stones over which a muller could be thrust back and forth. There are many sculptured models and pictorial representations in the Egyptian material, reaching back to the second millenium. Excellent plates are reproduced in Bennett and Elton, but it is hardly necessary to illustrate this most primitive mode of grinding. The Egyptian woman grinding

[66] MERCKEL, K. "*Ingenieur technik im Altertbum*," p. 538; NEUBERGER, "*Die Technik des Altertbums*," pp. 421, 425.

[67] SCHMIDT, "*Heronis opera*," Vol. III, p. 193, Fig. 83*b*.

knelt behind the thicker end of the saddle stone which sloped away from her and in this case ended in a small basin prepared to catch the flour. The muller was ovoid in cross-section, but rather flat: the ends were sharpened to make it easier to hold it in the hands without bruising them. The muller was pushed over the grain under the full weight of the body. The motions are in many ways similar to kneading, but the Egyptian figures representing kneaders can be distinguished from the grinders by the different degrees of effort indicated. Saddle stones are found among the remains of practically every primitive culture, and persist down to a late date. Schliemann held that only coarse grits could be prepared by such means, but it has been demonstrated conclusively that flour can be made.

The mortar was an improvement over the saddle stone, especially when the mortar was large and carefully shaped. In Greece and Rome this development proceeded rapidly and though the saddle stone survived in a small way, it ceased to be of much importance. The work of flour making passed from the hands of female to male slaves who came to be called "pounders" (*pistores*).

These two methods dominated the preparation of flour down to the second century B.C., when the revolving mill, or quern, appears in the records. There has been much confusion over the matter and many have been inclined to place the origin of the quern at an earlier date, some even presuming that it appeared during the prehistoric period in various parts of Europe. The earliest certain reference occurs in the writings of Cato the Elder (232–149 B.C.).[68] Curiously enough, these earliest references describe the rotary mill as turned by asses; but such stones could be turned by two strong men, and slaves were put at this task. The small quern is not explicitly mentioned until somewhat later. Varro ascribes the invention of the quern to the Volsinians, but these, like other attributions are involved in many doubts. We can only say that the beginnings of the new development may probably be placed early in the third or even in the fourth century B.C., and that considerable development took place prior to the early references to the mills turned by animal power.

The earlier form of the great quern as turned by men or asses is shown in Fig. 31,[69] which reproduces a mill found at Pompeii. The weight of the upper stone is carried by a spindle set in the

[68] This position is taken by both Bennett and Elton and by Lindet; there is extended critical discussion in both works.

[69] Bennett and Elton, Vol. I, p. 179.

lower stone. The upper stone was provided with an iron rynd which contained a socket that fitted the spindle and four perforated holes for the passage of grain just outside the spindle socket. The grain was put in the hopper at the top, slowly trickled through the holes in the plate, and was ground during its passage between the mill stones. The mill was turned by wooden bars set into the sockets at the side of the mill.

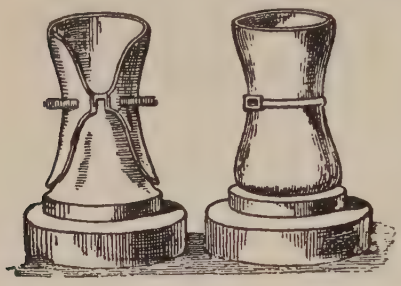


Fig. 31.—Great quern, Pompeii.

This type of mill is thus based upon the somewhat naïve idea that provision must be made for a direct downward flow for the grain and meal. The centrifugal action that takes place in the flattened and grooved stones is a distinctly more refined concept and must be deemed the more recent of the two. As there is no difference in form between the early slave mill and the mill turned by animals, it is perhaps not remarkable that the early references imply the use of animal power. The mill of the primitive type was heavy and invited the use of animal power. This is probably one of the earliest applications of animal power to industrial work.

The development of the light hand mill with flattened stones seems to have followed the invention of the conical-shaped quern with its downward flow. The centrifugal motion could not be fully developed until the mill stones were cut, and it is this feature of the new mill that makes it possible to identify it in the texts.

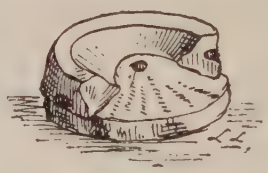


Fig. 32.—Hand quern, Innsbruck.

Virgil refers to mills turned by one hand, and to the dressing of the mill stones. The two items are a fairly certain basis of identification, and there are many vaguer references that are wholly comprehensible only upon the assumption that the light hand mill with flattened stones appeared on a substantial scale just before the Christian era. It is not possible to find examples that can be dated even approximately, but the general aspect of such a mill is shown in Fig. 32.[70] This specimen found at Innsbruck is

[70] Lindet, "*Les origines du moulin à grains*," *Revue Archéologique*, Vol. 36, p. 30, Fig. 17.

clearly a transitional type, whatever may be the precise date of its actual use. It is a small edition of the great quern for slaves or animals. The stones are smaller and considerably flatter. The upper stone has become a ring whose weight is borne by the rim. It is turned by means of handles set into a socket shown at the right. The grain still traverses a downward slope in the process of grinding. The ground meal is delivered by the opening shown on the left-hand side. No definitely new principle is involved, though the scale of the apparatus is altered. The specimens of Roman hand mills found in Europe can be arranged in sequence from the type shown above to the flattened stones with fully

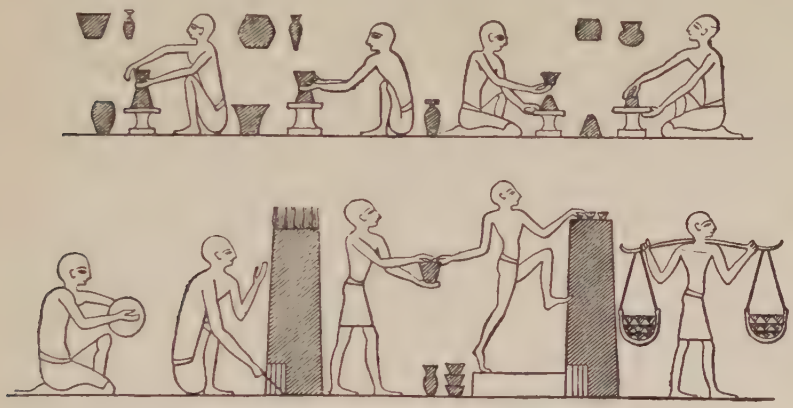


FIG. 33.—The potter's wheel, Egypt.

developed cutting. In view of the character of the archeological material, it would be hazardous to attempt any detailed analysis. The more active development seems to take place in the field of the small hand mill. The attempt to make a lighter apparatus resulted in various technical improvements. These, however, carry us well into the Christian era, so that here, as in other instances, we find evidence of notable technological changes in process about that time.

Reference has been made already to the early origin of the bow drill, first applied to the making of fire and later to a series of drilling operations generally based upon abrasion rather than actual cutting. Although these devices contain important elements of the lathe, the only basic improvement during antiquity was the potter's wheel. This appears in Egyptian reliefs in the Middle Kingdom and is presumed to be of great antiquity. Four potters

are shown at work in the picture reproduced in Fig. 33.[71] The clay is placed in the center of the mobile disk, and is shaped with one hand while the wheel is kept in motion by the other hand. In the Middle Ages, an arrangement was provided to turn the wheel by foot power transmitted from a treadle to the wheel. But though there is one passage in ancient literature which seems to suggest the use of foot power to turn the wheel, there is no supporting evidence. Modern writers hold that the wheel was turned by hand, throughout antiquity. Walters reproduces fragments of Greek vases of about 600 B.C. and 500 B.C. which show hand-turned wheels, and there is no ground for supposing that any changes took place in this phase of technical practice.[72] When a very large piece was undertaken the potter's helper turned the wheel, allowing him to use both hands on the work.

FIG. 34.—Egyptian bow drill.

The bow-string drill that was probably in use in prehistoric times remained the basic instrument for many purposes: carpenters, furniture makers, ship wrights, sculptors, gem cutters, all used this device for turning the tool. The earliest types of tool persisted in the work on the harder substances: the drill in such instances was merely the means of applying an abrasive suspended in oil or water. For coarse work on softer substances sand and water were adequate. In gem cutting, emery powder mixed with oil was the primary abrasive. Sculptors using relatively large drills required the assistance of a helper to draw the cords.[73] The best single representation of the bow drill is the Egyptian painting given in Fig. 34.[74] The drill is held with one hand. The cord is given a couple of turns around the drill and is operated by the other hand of the workman. Greek gems depict the device in the fifth century

[71] ERMAN-RANKE, "*Ægyptisches Leben*," p. 545; p. 230, upper figure.
[72] WALTERS, "History of Ancient Pottery," Vol. I, pp. 207–208.
[73] BLUMNER, Vol. III, p. 220.
[74] ERMAN-RANKE, "*Ægyptisches Leben*," p. 542, Fig. 228.

B.C. and a mortuary inscription and relief of the Roman Imperial period symbolizes the craft of the gem cutter by the bow drill.[75] There is thus an abundance of evidence against the old view which assumed that the technique of gem cutting in antiquity was practically identical with the technique of the eighteenth century. Blümner even reproduces plates showing the eighteenth-century lathe as a basis for the discussion of the Græco-Roman technique. This is perhaps one of the most striking illustrations of some of the older misconceptions of the technical proficiency of the pre-Christian world. The old technique is carefully described by Middleton. Besides the plain drill, the ancient gem cutters used a tubular drill, and also a wheel: both tube and wheel were made of bronze and employed a mixture of emery powder and oil. The wheel was mounted on a long, slender shaft of wood and worked by the bow: it was useful in cutting a thin line or a broad sunk surface. One striking difference is involved in this technique: the object to be worked was set firmly in a frame while the tools were moved about; today the tool is set in the gem-maker's lathe and the work is held against it. In this connection it may be well to emphasize the fact that there is no direct connection between the character of the tools and mechanisms used and the quality of the craftsmanship. The highest quality of work has been done with the simplest appliances. Ancient gem cutting was, on the whole, superior to the modern work. So too, periods of technological advance are not necessarily periods of improvement in the style or finish of the work. Many of the misconceptions of the technique of antiquity are due to the naïve assumption that good work implies elaborate tools and mechanisms. In a few fields, notably in the iron and steel industry, new technical processes have made it possible to produce results that are essentially superior. Particular qualities of steel and iron can now be produced and forms can be made that were really beyond the achievement of earlier ages. More frequently, technological advance merely reduces costs and opens up possibilities of a larger volume of production. We produce today different but no better linen or furniture than was made in ancient Egypt; we cannot produce any better porcelain than the early Chinese porcelain; nor can we make any better buildings than those of ancient Greece and Rome. We do have the means of producing a greater variety of things than was possible at that time, not only

[75] MIDDLETON, "The Engraved Gems of Classical Times," pp. 104*ff*; FÜRTWANGLER, "*Antike Gemmen*," Vol. III, p. 399, Fig. 206.

in these fields of production but especially in others, metal wares and glass. Technological improvement involves a substantial intellectual achievement, but it is not precisely synonymous with "progress." It is simply one part of a highly complex development which must be seen in relation to the whole. Separate analysis and description of many of the technological problems are nevertheless necessary steps toward an adequate synthesis.

The technique of spinning and weaving is one of the oldest accomplishments of craftsmanship. Substantial achievements took place in the prehistoric period and the accomplishments of the early historical cultures were very great.

Unfortunately, only a most fragmentary account can be given of the changes in the loom in antiquity, but some tentative results have been achieved, thanks to the careful studies of Braulik and H. Ling Roth. The serious defect in our present evidence lies in the absence of significant material for Mesopotamia, Asia Minor, and Rome. Under the circumstances, we are likely to think of Egypt as the only center of technical development, though important improvements may have been made in Asia Minor and Mesopotamia. The deficiency of Roman materials makes it almost impossible to describe or date the process by which the primitive European types of loom were supplanted by the superior eastern types. At the present time, therefore, we can only say that the superior types of loom were not originated in Greece or Rome. A notable development can be traced in Egypt. In ways not now known to us, much of this technique, which was probably also general to the Byzantine East, found its way into the European provinces of Rome in the early centuries of the Christian era; probably prior to the fourth century. It is not necessary to assume that the influence of the southeastern Mediterranean textile districts upon Europe was entirely consummated at so early a date. But these matters not only lead us beyond our present chronological limits, but carry us into conjectures and inferences that cannot now be supported by much concrete evidence. It is important, however, to recognize the deficiencies of our present materials. For the moment, no discussion of the processes of spinning is necessary as the hand spindle or "rock" persisted in Europe until the late medieval period, and the technique of spinning can thus be taken up most appropriately in a later chapter.

The pictorial representations of early looms are so deficient in detail and so ill preserved that considerable expert study is required

to interpret them. The originals of the Egyptian paintings cannot be very effectively reproduced by photography, and publications of these now famous paintings present an astonishing amount of variation. H. Ling Roth publishes the entire series together with new and larger drawings made especially for his treatise on the Egyptian and Greek looms. In this case, reproduction of the historical evidence itself is impractical in a brief survey for non-technical readers, whose needs can be better served by diagrammatic figures. The diagram shown in Fig. 35[76] represents the primary parts of a loom. These are the primary parts of a developed loom, present in one form or another in every loom except the draw loom which will be described in a subsequent chapter. The diagrams as

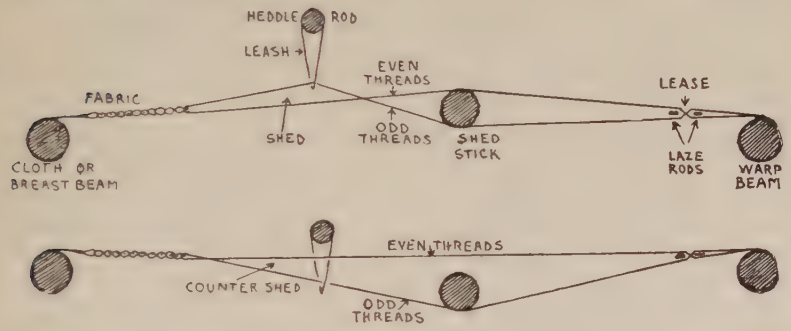


Fig. 35.—The primitive vertical loom: diagram.

drawn represent the essential features of the Egyptian loom of 1200 B.C. The warp is suspended vertically with the cloth or breast beam near the floor. All the motions were accomplished by the weaver or weavers so that there is really nothing eliminated. This diagram is thus, in fact, a schematic sectional drawing of the Egyptian vertical loom.[77] The process of weaving consists in interlacing at right angles to each other two sets of threads. In practice, one set of threads, known as the warp, is laid out in orderly array on some frame and subjected to enough tension to make them manageable. The cross-threads or weft are woven in by passing thread through the warp. In plain weaving, a rigidly alternative pattern is observed in the crossings of the threads. In one shoot, the weft threads pass over all the even threads and under all the odd threads; while in the next, the crossings are reversed.

[76] Roth, "Primitive Looms," p. 1, Fig. 1.

[77] Braulik, "*Ægyptisches Gewebe*," p. 62, Fig. 92 furnishes a noteworthy supplement to the diagram from Roth.

Weaving can be accomplished without great difficulty when the warp is merely set upon some kind of frame under tension. The weft may be passed through the warp without any particular tools, each individual thread being lifted or depressed as the case may be. The process is, of course, facilitated by the use of a flat wooden needle which is the progenitor of the shuttle. The chief need of the weaver, however, is some simple means of opening the warp so as to simplify the picking out of the odd and even threads, or any other sets of threads required by the chosen pattern. The adequate accomplishment of this purpose requires the three devices

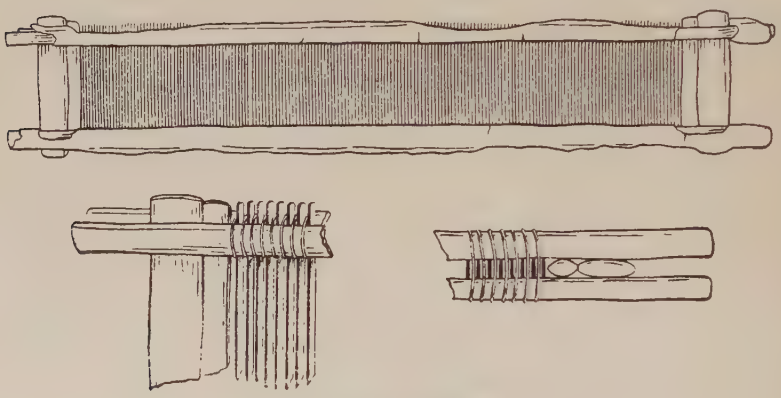


Fig. 36.—Coptic reed.

shown in the diagram: the laze rods, which separate the odd and the even threads and obviate snarls by means of the crossing; the shed stick, which opens the warp in a general fashion; one heddle rod attached to the odd threads, or if no shed stick is used, two or more heddle rods attached, respectively, to odd and even threads or to as many sets of threads as are required by the pattern. If the heddle rod and shed stick are drawn upward (forward, if the warp is placed vertically) an opening is formed between the odd and even threads of the warp in which the odd threads are uppermost. The shuttle or ball of weft may readily be passed through. The heddle rod and shed stick are then pushed back, forming an opening designated as the counter-shed, in which the even threads are uppermost. Two threads of weft would thus be laid in between the warp threads, but it will be obvious that they could not conveniently be placed close enough together to form a compact fabric. To complete the formation of the web, it is essential that

the weft threads be combed down close together. The simplest apparatus to accomplish this purpose is a hand comb, which would of course require the weaver to pass along the whole width of cloth at least once. The reed is a device for combing or beating in the weft along the whole length at one operation. The device shown in Fig. 36[78] was found in Egypt under circumstances which seem to identify it with the Copts (early Christians of Egypt). It consists of a loosely constructed wooden frame with flat iron wires, covered at top and bottom with canvas. These wires fit in between the threads of the warp, and, if placed just a little to the left of the heddle rod, the weft threads would be beaten in by drawing the reed frame up to the already completed web.

The other features of the diagram to be noted are the beams: the warp beam, and the cloth or breast beam. These are essential elements to a compact and convenient machine; but they are not, strictly speaking, necessary. In the early looms and in many primitive looms today in the warmer and drier countries, the entire warp is laid out in one piece along the ground. For the weaving of long pieces of cloth this has its inconveniences, but it is in many ways a simplification. It requires no little skill to prepare for a loom beam 40 yards of warp containing perhaps 70 or 80 threads. When the warp is stretched full length along the ground, this complex process is of course eliminated: the warp can be laid on directly thread by thread. This simplicity is purchased at a price, and the significant development of weaving requires the introduction of beams: one beam carries the warp threads, all rolled up in good order; the other beam carries the roll of completed cloth. As the shed stick shown in the diagram is really a simplified heddle rod, the primary parts of the loom are two beams, the laze rods, the heddles, and the reed.

Early weaving accomplished the necessary operations by means of makeshifts of various types; an astonishingly useful piece of apparatus can be contrived with loose sticks thrust through the warp in various places. One of the simplest types of loom consists merely of two posts and a cross-bar. The warp is hung from the cross-bar; tension is produced by attaching weights to groups of threads;[79] weaving may then be carried on with or without

[78] Roth, "Primitive Looms," p. 22, Fig. 25.

[79] Schematic pictures show them attached to single threads, but that is impossible, for the threads would then unravel, losing all the twist put into them in spinning.

heddles. This kind of loom is presumed to have been used in the prehistoric lake villages of Switzerland; Greek vase paintings of the sixth century B.C. indicate that it was the dominant form of early Greek loom; Herodotus, traveling in Egypt in the following century contrasts Greek and Egyptian looms in such a manner that it is evident that the vertical loom with weights was still in use in Greece. This type of loom shows some improvements in technique, as the heddles and laze rods appear in simple forms, but it was not a type that admitted of much development because it was necessarily limited to the weaving of short pieces. As the warp was held by weights at the bottom, it was necessary to weave upward towards the cross-bar. The cross-bar could not be higher than the convenient reach of the weaver and the length of the piece was thus narrowly restricted. This type, as such, therefore, contained little possibility of development. When the warp was put on a beam and another beam was provided for the finished cloth, it was more natural for the weaver to beat the weft in towards his body, if the warp were horizontal or downward, if the warp were vertical.

From the systematic point of view, the development of the loom reveals several fairly definite stages of development: plaiting, on a rigid frame or upon a vertical warp with weights; primitive weaving, involving horizontal or vertical looms with beams, shed sticks, and heddle rods; the developed horizontal loom with pedals and a reed; and the draw loom.[80] Although the vertical loom is capable of some significant applications in tapestry work, the process partakes of elements that are more closely related to embroidery than to weaving. Both vertical and horizontal tapestry looms represent modifications of an essentially primitive technique of weaving. The transition to developed weaving is marked by the improvements in the heddles and the contrivance of devices to enable the weaver to work them by foot power. Although this improvement completes the development of the hand loom for plain weaving, such a device may still be an extremely simple piece of apparatus. A loom of this general character employed by one of the native tribes of Liberia is shown in Fig. 37.[81] The reed is shown here, though in a much simplified form; it is intermediate between the beater or comb and the developed reed permanently set in the warp and attached to the frame of the loom.

[80] EPHRAIM, "*Entwicklung der Webe Technik*," pp. 11–26.
[81] EPHRAIM, "*Entwicklung der Webe Technik*," p. 29, Fig. 30.

The discovery of a reed in early Coptic burial grounds creates a strong presumption that the horizontal loom was significantly developed during the long period subsequent to the New Empire. It is presumed by many that the pedal attachments and the improved heddles appeared during this period, but there is no explicit evidence. Surviving fragments of textiles lend considerable weight to this hypothesis of a notable development in the technique of loom construction, but it would be possible to produce

FIG. 37.—Primitive loom with pedals.

many of the patterns upon a very simple apparatus. Consequently, we are not in position to declare positively that the loom with pedals had appeared in Egypt prior to the Christian era, though there was undoubtedly development in that direction. The technique of the textile districts of Asia Minor can scarcely have been inferior to that of Egypt, though the dominant fabrics were of wool, goat hair, and cotton, rather than linen. In the Græco-Roman world there is no evidence of any development beyond the primitive vertical loom with beams, laze rods, and heddle, which was still in use in Italy as late as the fourth century A.D. if we may accept the evidence of an illuminated manuscript of Virgil.

VI

The extent of the dependence of antiquity upon human muscular effort has recently been explained by the studies of Lefebvre des Noëttes. It appears that the methods of preparing animals for work were defective, particularly as regards horses and mules: the harness was ill designed and no adequate protection was provided for their feet. These deficiencies would undoubtedly diminish the efficiency with which animals could work, and there are a number of text references which indicate specifically that the expectations of the ancients fell far below modern standards of average daily accomplishment.

Xenophon in the Cyropedia and clauses in the Theodosian code state specifically the average tractive effort expected from teams of animals. Cyrus had built a mobile tower for siege work and seemed surprised that eight pairs of oxen could not move it more easily than the average baggage wagon. Xenophon remarks that "the ordinary load of baggage wagons drawn by a pair of oxen was about 25 talents (1,452 pounds)," though the towers imposed no more than 15 talents of effective load per pair of oxen. The Theodosian code fixes the net load of the light wagon (Rhæda), at 1,000 Roman pounds (680 English pounds): the net load of the heavy wagon (Angeria or Clabula) at 1,500 Roman pounds (1,002 English pounds). The latter figure is the more significant for comparisons, as it implies slow transport with walking animals. Assuming Xenophon's figure to be for the gross load, his expectation of average daily work is roughly consistent with the clause in the Theodosian code, for the wagons of antiquity were relatively lighter than ours. Lefebvre des Noëttes estimates them at roughly one-half the effective load.

Such standards of expectation are vague and ill defined at the best. There are, of course, wide variations in the capacity of particular animals; considerable variations in the conditions of work; sensible differences between maximum possible performance and the performance consistent with the continued efficiency of the animal. However, the text figures just cited seem to be made from the point of view that is of concern to the engineer in figuring the average work that can be expected in the long run under conditions that are not particularly favorable. As the discussion involves the relative capacities of the various animals the presumptions embodied in the following table will contribute important data.

MUSCULAR POWER OF A MAN AND OF VARIOUS ANIMALS

(Values of the greatest day's work)[82]

1 horsepower = 33,000 foot-pounds per minute or 500 foot-pounds per second

	Pressure–exerted: pounds	Velocity: feet per second	Foot-pounds per second	Ratio
Average draught horse	120	3.6	432	1.00
Ox	120	2.4	288	0.66
Mule	60	3.6	216	0.50
Ass	30	3.6	108	0.25
Man, pumping	13.2	2.5	33	0.076
Man, turning winch	18	2.5	45	0.104

The primary heavy draft animal of antiquity was the ox. The horse was used chiefly for light work in which speed was essential. Reliefs suggest that the types of horse most common were the lighter and faster harness and saddle horses. The heavy draft animal of the nineteenth century was certainly a great improvement on the earlier types. The comparability of ox and horse as to strength that is assumed in the table given enables us to discount some of the influences of the work of the great animal breeders. The bovine races have been improved, but hardly in the same degree. At all events, the comparison primarily important to the economist is the muscular efficiency of the animals of antiquity, irrespective of the specific factors involved: the explanation of the facts is, after all, a separate problem. Comparable figures for human exertion have been included in order to afford a basis for consideration of the entire problem. It should be noted that the pressures exerted here are effective pressures as recorded by dynamometer, not the weights transported. We may most readily compare a windlass or winch worked, respectively, by animals and men. It is now recognized that the horse works at a disadvantage if driven in small circles, so that the tractive power that can be exerted in a straight line can be secured only if the diameter of the circle worked by the winch is as great as 40 feet. Pictorial representations of early attempts to apply animal power to the mill show an arrangement that would have been very inefficient if literally constructed as indicated. The modern test figures thus show that the average horse would perform ten times as much work in a day

[82] RANKINE, "Useful Rules and Tables," pp. 251–252.

as an average man, and the other animals in proportion. It should be noted that some continental figures for mules and asses rate them higher than they are rated above. Argentine mules are rated very close to horses, and Spanish and French mules at rather more than 80 per cent of the capacity of the horse. The camel is rated at more than twice the strength of the horse.[83]

The capacities for tractive effort measured in terms of the useful load transported on level ground are, of course, subject to many elements of error, but they are essential to the interpretation of the figures of Xenophon and the Theodosian code. The following figures represent the late nineteenth century engineering expectations of continuous daily performance.

TRACTIVE EFFORT OF MAN AND HORSES

(Net loads transported horizontally)[84]

	Net load drawn or carried, pounds	Velocity, feet per second	Load conveyed horizontally, 1 foot per second	Ratio
Horse:				
Walking with cart always loaded.	1,500	3.6	5,400	100
Carrying burden:				
Walking.....	270	3.6	972	17.9
Man:				
Wheeling load in a two-wheeled barrow.....	224	1.66	373	6.9
Wheeling load in one-wheeled barrow.....	132	1.66	220	4.1
Carrying burden.....	90	2.5	225	

The comparative efficiency of working with or without wagons is significant, especially for horses, amounting to a reduction of efficiency to one-fifth. This comparison is of further significance when we consider the figure for antiquity of a net useful load of 500 pounds for transportation at a walk. We may say, therefore, that the net effectiveness of ancient draft animals in harness was not more than one-third of the modern expectation. The figures in the modern table are distinctly low; this is shown by the fact that the horse is rated for less than the unit called a "horsepower," and

[83] CLARK, "A manual of Rules, Tables, and Data," p. 721.
[84] RANKINE, "Useful Rules and Tables," pp. 251–252.

there are besides many details of higher performances. The rough statement, then, that animals in antiquity achieved only one-third of the modern expectation is really a moderate statement; under- rather than overstated. The discrepancy between the useful work of the larger animals and men was correspondingly less than now.

The extent of this failure to secure the full effective power of animals makes the explanations of Lefebvre des Noëttes especially timely. Unless it were possible to indicate concretely serious failures in ancient arrangements, one would hesitate to accept the findings, despite the quality of the evidence. The possible inferiority of the races of animals is not discussed by Lefebvre des Noëttes: it is clearly beyond the scope of any possible treatment, but the existence of such a factor should not be ignored.

Of the ponderable factors, the most serious was the positive inefficiency of the harness devised for the horse. Pictorial representation is specific. Throughout the Mediterranean world, and during the entire period of antiquity, two serious errors were made in the harness. The point of attachment was the back of the horse's neck, and the collar or band was set high on the throat instead of being lowered to rest on the shoulder blades. The position of the collar is not unrelated to the utilization of the yoke attached to the top of the collar. Traction exerted from such a point would inevitably pull any light leather apparatus high up on the throat, and apparently the ancients decided to locate the collar once for all in the only stable position possible under the circumstances. The result is, of course, disastrous under any heavy tractive effort. The pressure of the collar chokes the horse more or less; he rises on his hind feet to relieve the pressure; and under such conditions it is simply impossible to secure the advantage of more than a fraction of his actual muscular powers. The collar or breast plate should rest on the shoulder blades; the points of traction should be low; located preferably on each side of the body, just above the fore shoulders. Tractive effort exerted from such points of attachment tends to hold the collar in place against the shoulder blades, and enables the animal to throw the weight of his body into his work.

The ox was less inadequately harnessed. Simple forms of the yoke appear at an early date, attached either to the horns or laid across the neck. In some respects, early arrangements seem to be less adequate than later developments, but the differences were not great. As the ox was the primary heavy draft animal it is hardly

surprising to find that the power of the ox was more effectively utilized than the power of the horse. The difficulties in this case were confined to the absence of any protection for the feet. In plough land this was perhaps not a serious handicap, but for general haulage on hard roads it would quickly become a limiting factor. The evidence regarding the harnessing and shoeing of oxen is less adequate than that for the horse, but there seems to be no ground for doubting the general fact of impaired efficiency.

Many nineteenth-century writers held that the practice of shoeing horses was general in the Roman Empire. Many nails and horseshoes are exhibited as Roman in the museums of France and Germany. These exhibits are ill authenticated. The conditions of discovery were not carefully controlled and the places where the finds were made admit of later origins for the relics. In none of the purely Roman or Celtic sites have any nail set horseshoes been found. At present, the better opinion is in favor of the contrary view, which regards the horseshoe set with nails as a development subsequent to the decline of Roman power in the West. There is no evidence whatsoever of the use of such devices prior to the Christian era.

The foot protection used in antiquity was the sandal of leather or iron bound to the horse's hoof by thongs of leather or cords. The sculptured relief of the veterinary (*mulomedicus*) shows one form of these horse sandals. It is now held that these were used rather to cure foot troubles than systematically to protect the feet of working animals. In modern experiments with reproductions of the ancient device the sandals worked loose when the animal was set to heavy tasks.

The use of draft animals was further qualified by the insufficiency of the devices for harnessing more than one pair of animals. For many purposes the attempt was made to increase the power by putting several teams of animals abreast. Thus, the two-horse chariot was expanded into a four-horse chariot, with rather doubtful gain, as possibilites of control were adversely affected. A few attempts were made to use pairs of animals in file, but they do not seem to have been successful. The most notable single sketch of such an arrangement is the Egyptian wall painting at Tourah which represents three pairs of oxen drawing a large stone on a sled. The published drawings of this painting were so discordant that Lefebvre des Noëttes had the painting photographed, and upon this basis he has essayed a reconstruction of the device.

Even his solution does some violence to the original as represented in the photograph, and no wholly adequate solution seems possible. In the absence of other confirmatory evidence, this particular painting is hardly an adequate basis for the view that use was regularly made of teams harnessed in file for the hauling of heavy weights. Haulage with animal power was normally confined to relatively small units, and the large, heavy tasks were performed by the massing of large numbers of men. The relative advantage between animal and man power was further affected by the relatively high costs of maintaining draft animals in the drier Mediterranean countries. To what extent this factor would effect the issue it is impossible to say, but it should not be neglected. In view of the qualifications in the general utility of draft animals, the choice tended to lean very heavily in favor of man power. With conditions as they seem to have been in pre-Christian antiquity this emphasis on man power was natural. To some extent, this tendency must have discouraged attempts to devise machinery for applications of animal power, and to that extent the inability to use animals effectively in simple ways prevented and obstructed the development of more complex mechanisms. Antiquity had at its effective disposal only the lowest power units, with only the smallest extensions beyond the field of human muscular effort. This is in keeping with the known facts about mechanical appliances. We hear much about pulleys, levers, wheels, and their combinations; but almost exclusively in devices for the use of man power. The mechanical achievements of pre-Christian antiquity are concerned with the study and control of motion. Fundamental theorems were worked out sufficiently to meet the practical needs of many centuries. Facility in the production of motion was developed to a considerable degree. There is just one notable deficiency: no form of crank motion appears in any of the evidence. Nearly all the elementary pairs appear. We find the five other kinematic "chains:" the *screw* chain, the *wheel* chain, the *cam* chain, the *ratchet* chain, and the *pulley* chain. The *crank* chain only is missing. The treadle attachment to produce rotary motion is the earliest form of this type of mechanism; it does not appear until later. We may thus say that this period is concerned with fundamental statements of elementary principles and with the study of motion. The development and applications of power involved changes in scale rather than changes in principle. Consequently, the development that follows may seem to be little

more than a diffusion of knowledge already attained. For a long time, no additional theoretical knowledge would have been of much practical use. It would be an error, however, to minimize the magnitude of the technological changes that opened up the first extensive applications of power. It was the beginning of an essentially new stage in mechanical technique.

Chapter V

THE DEVELOPMENT OF WATER WHEELS AND WINDMILLS: 150 B.C.–1500 A.D.

I

The simplest form of the application of water power to grinding is found in a kind of mill that cannot be identified with certainty earlier than the fifth century A.D. The parts are described in the collection of Irish laws known as the "Senchus Mor" whose origins are ascribed to the time of St. Patrick, though written versions are considerably later. This kind of mill was certainly in use in every portion of Europe in the Middle Ages and in the thinly settled districts its use has continued to the present day. Bennett and Elton hold that this type of mill was really invented in Asia Minor early in the first century B.C. and spread thence to Italy and Northwest Europe; they thus call it the Greek or Norse mill. The grounds for this inference are not very secure, but it is certainly the best account that can now be given of the matter and it is, at all events, desirable to recognize the importance of this simple device for the application of power. In view of the character of available evidence about mechanical appliances, it is hardly surprising that our evidence is unsatisfactory, and, under the circumstances, it is extremely dangerous to adopt a rigid attitude toward the sources. For the moment, the historical questions may best be postponed.

The general features of these mills are shown in Figs. 38 and 39. Figure 38 represents the shaft of a mill found in a bog at the Grange of Drumtullogh.[85]

"The nave of the water wheel and the upright shaft are cut out of one solid piece of oak, the entire length being 6 feet, 6 inches. Round the nave are inserted nineteen curved vanes of oak, ten of which were found intact. They are fixed into the nave by mortices and further secured by oaken pins. At the top of the shaft is shown the simple arrangement for gauging the position of the upper

[85] BENNETT and ELTON, Vol. II, p. 15: from the *Ulster Journal of Archeology*, Vol. IV, p. 6.

stone, this being nothing more than a vertical groove or slot, in which was fitted a wedge for raising or lowering the top stone."[86]

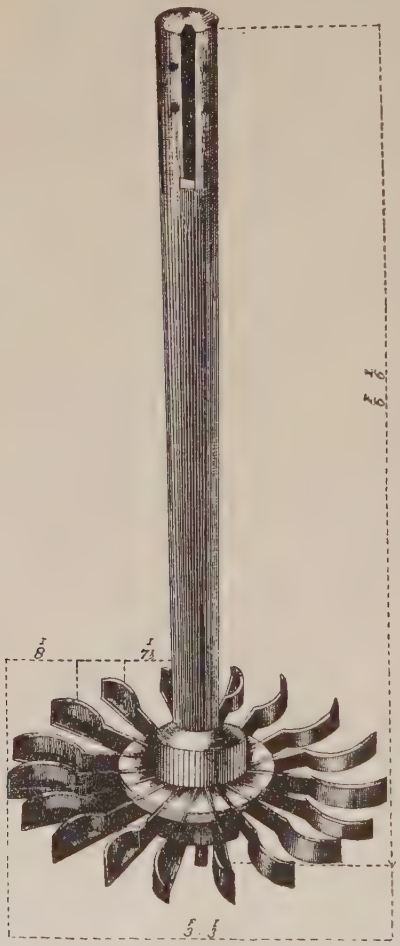


Fig. 38.—Shaft of an early horizontal water wheel.

The stone was fastened into the end of the shaft to serve as a pivot and the whole mechanism rested upon a stone placed in the bed of the stream. There is nothing to suggest that these remains are of remote antiquity. But they are a significant supplement to general descriptions or illustrations such as are available in the fifteenth century in the drawings left by a German military engineer (*c.* 1430) of the time of the Hussite wars.[87] The apparatus can best be understood from the drawings and photographs of recent mills of this type. A very simple form found in current use in the Shetlands in the late nineteenth century is shown in Fig. 39.[88] The diagram is oversimplified so that the attachment of the shaft to the upper mill stone is not shown. Iron fittings set into the upper stone fitted into a groove in the shaft and communicated the motion of the wheel to the stone. The water wheel as shown in this illustration is small: the central spindle is about 18 inches in diameter, the simple vanes are formed of boards 8 inches broad and 1½ feet long. The mill stones would rarely exceed 3 feet in diameter. The stone would make approximately

[86] Bennett and Elton, Vol. II, p. 15.
[87] Beck, G. M. B., p. 279, Fig. 324; also plates in Ramelli.
[88] Bennett and Elton, Vol. II, p. 21.

100 revolutions per minute, but as the stones were rarely cut they ground slowly.

The merits of such apparatus lay in the small amount of water required and the slight outlay in labor and materials. They were housed in tiny buildings of the simplest construction and could be put together by any carpenter. The mill itself could be built in a week, and the value of the entire equipment was very small. Consequently, large numbers of such mills may be found in districts well supplied with the tiny water powers necessary, for there was no great waste involved even if the mill stood idle for considerable

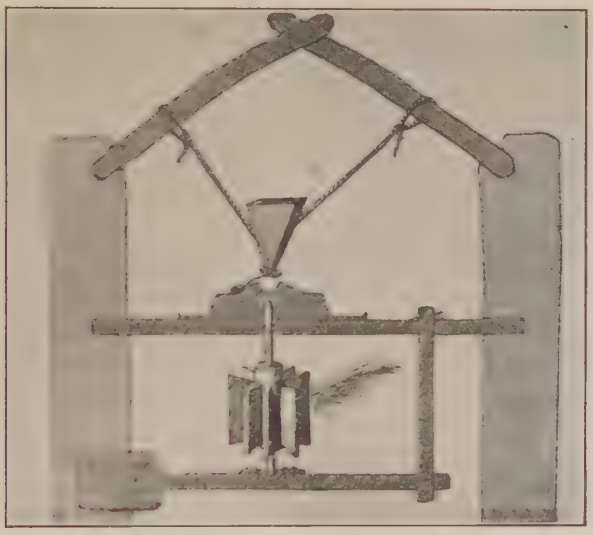


FIG. 39.—Horizontal water wheel: Shetlands.

intervals. No special skill was required to operate such mills and thus there was no specialization of milling as an occupation. At times, mills were owned in common; more frequently they were owned privately, but used by others than the owner for a small toll. The door would stand open. The customer attended to his own grinding. If we may assume that these features of the use of the mill were persistent throughout its history, this type of mill can be identified in the milling laws of the Teutonic codes; it is also probable that important inferences can be drawn from the differences in the law of mills that develop in the feudal period.

In one instance, Vitruvius (*c.* 16 B.C.) contributes a description of a machine that does not appear in any form in any of the Greek

treatises on mechanics; this unique contribution is the description of a geared mill. Some writers have spoken of Vitruvius as the inventor of this type of mill, largely on the strength of the fact that it does not appear in any other treatise. But this inference is not warranted by the text, in which the mill appears merely as one of various notable and somewhat unusual mechanical devices. The description in the text is faithfully reproduced by the drawing in Fig. 40.[89] An undershot wheel is mounted on a shaft which carries a toothed wheel fitted to another toothed wheel on the shaft of the mill stones. The stones are presumed to be of the type then commonly in use. The mill thus sketched is the first known instance of the transmission of power through gearing: distinguishing power used for a substantial task from the motions produced in cyclometers. This mill must, therefore, be regarded as the significant beginning of power mechanisms. The mill without gears was incapable of development or generalization. The geared mill inspired many modifications and rearrangements which resulted ultimately in an extensive generalization of the use of power.

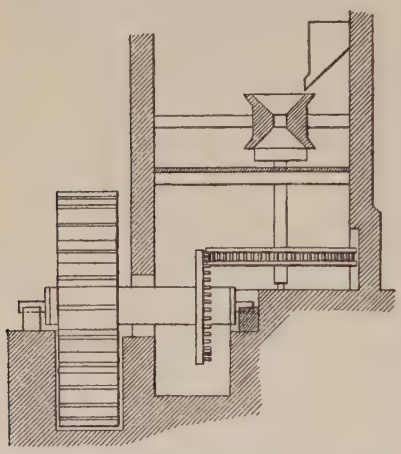


Fig. 40.—Roman mill with gears: after Vitruvius.

In the "Greek" or "Norse" mill, the absence of gears made the rate of revolution of the stones a direct function of the rate of flow of the stream used; there was thus no means of producing the speed required for the best efficiency of the mill. Once gears were introduced, the design of the mill could be adapted to the stream on which it was located. The mill as described by Vitruvius would not be impracticable on the Tiber, which is fairly swift, but it

[89] Beck, G. M. B., p. 49, Fig. 56. A concordant plate is given by Bennett and Elton, Vol. II, p. 33, but it is not so suitable for reproduction. Many of the illustrations of this mill, however, do not follow the text in regard to the relative proportions of the gears. The toothed wheel on the shaft of the mill stones is represented as being small, whereas the wheel on the shaft of the water wheel is represented as being large. This is contrary to the description in the text.

would be utterly useless on many streams. In later practice, partly to meet different conditions, partly as result of better knowledge of the problem, the proportions of the gear wheels were reversed: the crown wheel was mounted on the shaft of the water wheel, and a pinion or lantern wheel was mounted on the mill shaft. The mills were thus worked up to higher speeds. The change was complete as early as 1169, when a drawing of a water mill appears in the "Hortus Deliciarum" of the Abbess Harrad of Landsperg.[90] This is, in fact, the first known drawing of a mill subsequent to Vitruvius, and though external views of mills are available in the twelfth century this is the only illustration that shows the gearing. Many of the fundamental changes in the design of the mill are thus unknown to us and we have little hope of recovering any knowledge of the substantial development that took place in that long period in which the Roman mill had been introduced into all parts of northwest Europe.

As it is necessary to make considerable use of early medieval drawings and miniatures which are defective in many ways, it is important to note that we may regard most of these deficiencies as mistakes in drawing. In the mechanisms of the tower clocks that survive from the beginning of the fourteenth century, we have sufficient evidence that technical proficiency is not adequately rendered by contemporary drawings. Not until the close of the fifteenth century do we find drawings free from crude errors in perspective, and even many of the woodcuts of the sixteenth century leave much to be desired. We are justified therefore in using these early drawings as means of dating the appearance of particular devices.

We have no positive indication that the Romans made use of the overshot wheel. The text of Vitruvius implies the use of power applied to the lower part of the wheel only, as in the noria when driven by the force of the stream. The descriptions of later Roman mills and the use of water from the acqueducts on the Janiculum would suggest the possibilities of the technically superior overshot wheel, driven by a stream of water led by a sluiceway to the top of the wheel. In such a wheel the weight of the water as well as the speed of the current is utilized. Explicit illustrations of overshot wheels do not occur earlier than the middle of the fourteenth century. Several crude, but explicit, drawings occur

[90] Herrad von Landsberg, "*Hortus Deliciarum*," Plate, xxx.

in an illuminated Ms. of the Sachsenspiegel,[91] and in view of the character of these sources this date can hardly be assumed to represent the date of the invention of this device. In this connection, however, the number of illustrations of undershot wheels from the twelfth to the sixteenth century shows that the overshot wheel was the less usual of the two forms.

The general mechanism of the geared mill was also adapted to the use of other forms of power, notably hand power and horsepower, and although this may seem to be a step backward to the use of muscular energy, from another point of view it is really a step forward toward a wider generalization in the application of power. The amount of power involved is not large, but these means afforded facilities for the production and application of modest amounts of power that were of substantial industrial importance. One of the illustrations of the Psautier de St. Louis (late thirteenth century) shows the essential mechanism for the use of man or horsepower as a driving force. The lantern is engaged by the teeth of a very large wheel which in this illustration is pushed by a man.[92] The drawing is too defective to be worth reproduction, but the identification seems to admit of no doubt. Similar mechanism for the application of horsepower appears in the notebooks of the Hussite engineer (*c.* 1430) which have been studied by Beck. The perspective of the drawing is faulty, but the identification is beyond doubt, and additional interest is furnished by the arrangement of the device to drive two mills. The fifteenth-century drawing is reproduced in Fig. 41.[93] The identification of the device as the horse gin or windlass is made certain by the cross-bar on the upper portion of the driving shaft.

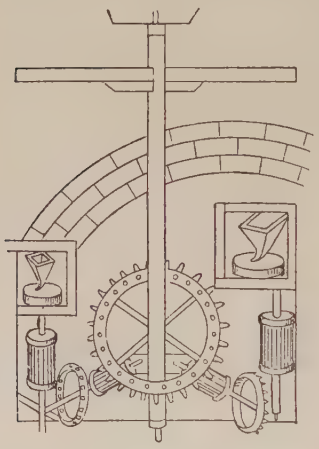


FIG. 41.—Horse mill, about 1430.

[91] AMIRA, K. VON, "*Die Dresdener Bilderhandschrif des Sachenspiegels*," Plates, 66, 69, and 101; see also, *B. G. T. I.*, Vol. X, p. 178, Fig. 7.

[92] Bibliothèque Nationale; Dept. des Mss. PSAUTIER DE ST. LOUIS, Ms. Latin, 10525. Plate 62.

[93] BECK, G. M. B., p. 277, Fig. 319.

The apparatus is shown in more explicit form in the somewhat later drawing by Georg Agricola.[94] The form suggested by the drawing in the Psautier de St. Louis and the application to the mill is explicitly shown by a sixteenth-century German engraving reproduced by Bennett and Elton without indication of its source. This application is shown in Fig. 42.[95] The construction of the driving wheel, and the arrangements for contact with the lanterns driving the mills are all closely similar to the crude thirteenth-century sketch. We are thus in position to affirm with certainty that this generalization of the application of gearing to various sources of power was well launched as early as the thirteenth century. The

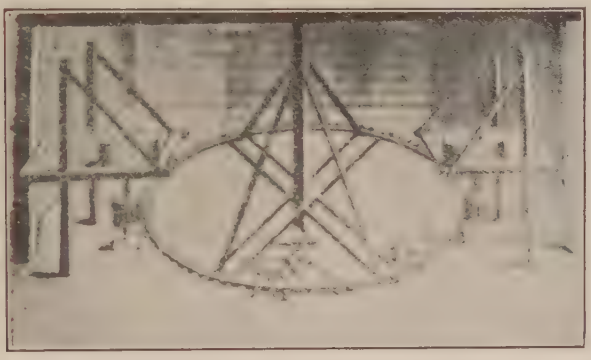


FIG. 42.—Horse mill, sixteenth century.

development was due, in part, to the inconveniences of the variations in the flow of water and to the need of power in places and under circumstances which did not admit of application of water power. The development of the water mill thus reacted upon the old horse and slave mills and resulted in a more sophisticated use of the primary sources of muscular energy.

These devices were all concerned with pure rotary motions; the development of crank motions for the conversion of reciprocating motion into rotary motion was a technical step of a more original type. The earliest drawing now known of such a device appears in the Ms. of the engineer Konrad Kyeser (*c.* 1405).[96] The drawing is in bad perspective and some of the details are less clearly shown than in the drawing of the slightly later Ms. of the

[94] GEORGIUS AGRICOLA, "De Re Metallica," ed. Hoover, p. 167. Reproduced in somewhat simplified form by BECK, G. M. B., p. 132, Fig. 146.

[95] BENNETT and ELTON, Vol. I, p. 197.

[96] *B. G. T. I.*, Vol. XI, p. 181, Fig. 4.

Hussite engineer (*c.* 1430), which is reproduced in Fig. 43.[97] The mechanism of levers is simpler than in the Kyeser drawing, but the crankshaft is more completely shown here. We must assume that simple treadle motions were known prior to this date, though it is surprisingly difficult to find explicit drawings. These drawings probably carry us well back toward the beginnings of crank shafts and crank motions, which rapidly come into general use in the fifteenth century. How much earlier these devices were known cannot now be determined.

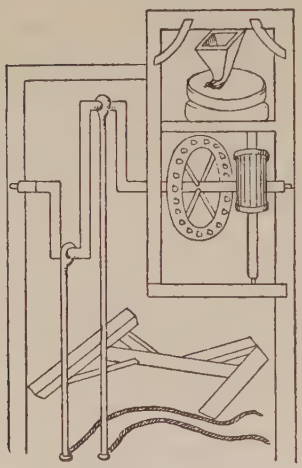


FIG. 43.—Mill with crank drive, about 1430.

II

The use of the wind as a source of power in Europe is not established by any authentic contemporary document, earlier than the close of the twelfth century. The Arab geographer al Mas 'udi, who made extensive travels between the years 915 and 943, speaks of seeing windmills in Persia.[98] Reference is also made to windmills by al Farsi al Istakri, another Arab geographer of the tenth century.[99] But there has been much unwillingness on the part of European writers to accept the idea of an eastern origin of the windmill, largely because little use is today made of them in the East. It is possible that the wind was used at an early date in Thibet to keep prayer wheels in motion,[100] and if this were indeed the case it would throw much light on the early history of the use of wind power in the East. It must not be forgotten that there is a description of the use of wind power in the treatises of Hero of Alexandria. The development of the windmill of the Middle Ages may have originated in several ways, and in the present state of our knowledge it is idle to speculate about details. It should be noted, however, that much attention must be given to

[97] BECK, G. M. B., p. 276, Fig. 317.

[98] SARTON, "History of Science," p. 638, note.

[99] SARTON, "History of Science," p. 674.

[100] REULEAUX, p. 207–208. The reference to Lazarus Geiger is without page number and it has not been possible to locate the passage or to find other support for the statement.

the source of statements of origins, for in this connection there are a number of misleading references which attribute early dates to windmills. There are two charters purporting to be of 833 and 1105, respectively. The first of these purports to have been granted to the Abbey of Croyland by Witlaf, King of Mercia. The charter is now held to be a forgery of the time of Henry II. The second charter, of 1105, purports to be a grant to the Abbey of the Holy Trinity of Newburg, but it is now held to be a forgery of about a century later. The chronicles are a more dangerous source of information. A Welsh chronicle by Iolo Morganwy attributes a date of 340 A.D. to the introduction of water mills and windmills in Wales. A fifteenth-century history of St. Augustine's at Canterbury alleges the use of a windmill in 669 A.D. A sixteenth-century chronicle of Bohemia declares that windmills were used exclusively until 718, when water mills were introduced.[101] Bennett and Elton are unwilling to accept the opinion long common that the windmill was introduced into Europe by crusaders returning from the East, but the notion of an Eastern origin is materially strengthened by the apparently established facts that the device was known in the East in the tenth century and rather widely diffused in England and northern France at the close of the twelfth and the beginning of the thirteenth century. It is, however, fairly certain that windmills appeared in Europe prior to the Crusades.

There are no pictorial representations of windmills prior to the fourteenth century and all the early drawings are so small and incomplete that they barely suffice to identify the outstanding external features. But these drawings are not without significance, because some of the distinctive features of the windmill are wholly external. The windmill involved one mechanical problem that was wholly new. In order to present the sails directly to the wind, the whole structure or some substantial portion of it must be mounted on a pivot so that it may be easily turned about. Two distinctive types appear: the smaller mills which revolve around a central post which is more or less permanently attached to the ground; the larger mills, which consist of two parts, the main tower which is rigid and a turret at the top which is moveable and carries the main driving shaft and the sails. All the early mills are variants of the post type: some mills were entirely supported by a tripod with cross-beams resting upon the

[101] Bennett and Elton, Vol. II, pp. 224–234.

surface of the ground with no more attachment than was furnished by a few pegs; other mills were firmly attached to the ground, the central post being sunk and set in an appropriate foundation. Both types are very old but the tripod type appears to be the older. The fourteenth-century representations are of that type, as also the diagrams furnished by the notebooks of the Hussite engineer (*c.* 1430). One of these diagrams is reproduced in Fig. 44;[102] presenting one of the earliest sketches of the parts of a windmill. The structure is supported by a tripod which rests somewhat off center on some heavy planks. The sails are fastened to a driving shaft which is here shown as set horizontally to the ground. No details of mechanism are shown for raising or lowering the stones or for the control of the mill. Some means must have been available for raising and lowering the stones in order to adapt the mill to the different grades of grist and flour to be prepared; but we have no information to warrant any specific suggestions for the completion of the drawing. The lever used to turn the mill is indicated at the left. In the course of another century we have practically positive knowledge of the appearance of some of the fundamental refinements—the brake and the inclination of the sail beam to the horizon. In the drawings of Agricola's "De Re Metallica," 1556,[103] hoisting apparatus was controlled by the pressure of a simple beam applied to a beam on the driving axle. Beck infers that no better means were available for controlling windmills. Leonardo de Vinci sketched curved brake bands to be applied to the driving wheel itself,[104] and this device seems to have found its way into use in the course of the sixteenth century for it appears in the work of Ramelli published in 1588.[105] The desirability of setting the sail beam at an angle to the horizon is discussed at some length by Jerome Cardan in his attempt to analyze the mechanics of a windmill. We may thus

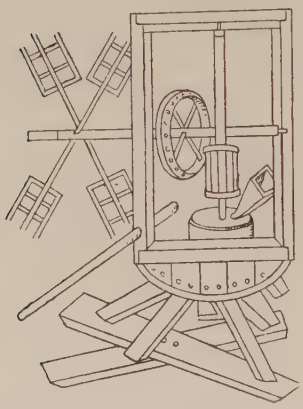


Fig. 44.—Post wind mill, about 1430.

[102] Beck, G. M. B., p. 278, Fig. 321.
[103] Beck, G. M. B., p. 132, Fig. 146.
[104] Beck, G. M. B., p. 328, Fig. 421.
[105] Beck, G. M. B., p. 221.

infer that the increased efficiency from such an arrangement began to be commonly known at least by the beginning of the sixteenth century. There is thus no clear evidence that the windmill was developed to a stable and efficient form much before 1500. There is some danger of underestimating the quality of the earlier work, but it is hardly justifiable to assume that errors in drawing go beyond matters of perspective and arrangement and in that case the Hussite drawing indicates a mill that is lacking in much refinement. For purposes of comparison, a diagram of a modern mill is reproduced in Fig. 45.[106] There is little ground to suppose that the mill here shown differed significantly from the tripod or post mill of the early sixteenth century. The inclination of the axle *A* is not very conspicuous but it will be evident on close inspection. The brake band *G* is clearly shown. The combination of levers for regulating the height of the stones can be seen in part—at *LMOP*, though important features are hidden behind the control posts. It will be clear that the windmill is a rather more complex mechanism than a water mill of equivalent power, and it is of course for that reason that its development is so much slower.

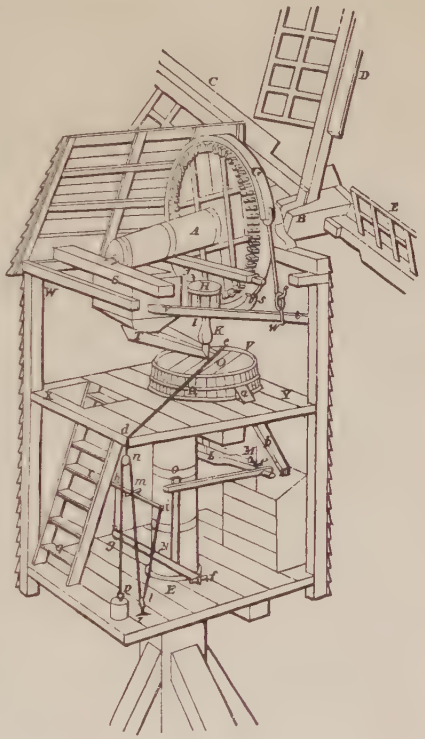


FIG. 45.—Modern post mill.

Increase in size was strictly limited if it were to be necessary to turn the entire building to head the sails up into the wind. The larger mills are thus of the tower or turret type. Such a modification of the mill is suggested by sketches in the notebooks of Leon-

[106] NICHOLSON, "The Operative Mechanic," Plate 12, Fig. 123.

ardo da Vinci[107] and a complete mill is shown in Ramelli's work, but the general development is commonly associated with Dutch engineers of the late sixteenth century. But these changes were changes in size and in refinement of design that added to the efficiency of the mechanism without greatly transforming its primary characteristics.

III

Attention has already been called to the adaptation of the geared mill to the use of animal power and there is an abundance of material to show that such sources of power were not in any general sense supplanted by the development of water power. The limitations imposed by the location of waterfalls and rapids made animal power an important resource for many purposes, and it is therefore a matter of substantial moment that notable improvements were made in harnessing horses and in protecting their feet. It has already been shown that only a limited use was made of animal power in the pre-Christian period. Horses could not be used with any significant efficiency, and though cattle could be used to a limited extent, their effectiveness must certainly have been subject to some restrictions. The development of the geared mill offered new opportunities, and the development of more effective harness changed decisively the relative values of man power and animal power. How much this development was stimulated by the relative dearth of man power in northwest Europe we can only surmise. This entire development of power mechanisms was possibly fostered by the relative scarcity of labor in these sparsely settled districts. The diffusion of population over large areas created economic problems that were essentially different to those of the densely settled regions of the Near East and the Mediterranean regions which had dominated history throughout the pre-Christian period. Labor conditions on the frontier are thus essentially favorable to certain kinds of innovation. It is possible that technical knowledge may be less considerable, but the economic need is much greater, and once the rudiments of practical mechanics have been mastered the incentive to the substitution of mechanical devices for direct labor becomes very strong. In the employment of animals, further factors were

[107] Beck, G. M. B., pp. 327–328, Figs. 419–420. See also, Ramelli, "*Li artificiose machini*," p. 205, Fig. 132.

involved. Conditions of Mediterranean agriculture are not wholly favorable to stock raising. The long dry summer is a serious handicap, commonly met by the development of the regular migrations between summer and winter pastures that characterized stock farming in Italy and Spain for centuries. The stock kept on the farm for farm work tends to be reduced to an absolute minimum. In northwest Europe, the relatively humid conditions created different relations between livestock and the farm. Under the circumstances, therefore, it is scarcely surprising to find more extensive use of animal power in North Europe and thus the effective use of such powers became a matter of more importance than in the Mediterranean world. It is noteworthy that relatively efficient harness for horses appeared in China under the Han dynasty (200 B.C.–300 A.D.). One may presume that the development of effective harness was largely a matter of the pressure of necessity and the relative use made of animals, so that the ineffectiveness of ancient harness may be attributed in part to the fact that there was no disposition to make extensive use of animal power.

Evidence of a decisive change in the mode of harnessing horses appears in illuminated Mss. of the first half of the tenth century. The center of traction is moved from the back of the neck to points just over the shoulders. The yoke is thus supplanted by traces or tugs in practically the modern position. The neckband of the ancient harness becomes the light breastplate of modern harness which locates the pressure of tractive effort across the chest instead of high up on the neck where it would press on the horse's windpipe.[108] Apparently, the new harness did not immediately supplant the older style for the new mode is not dominant in illustrations in either the tenth or the eleventh centuries. By the twelfth century, the transition was complete and the harness had been perfected. We see in that century the heavy padded collar fitted to the shoulder blades, and the traces were attached to a whippletree instead of being fastened directly to the wagon itself. There is no indication of the arrangements made for backing or holding the load back on hills, doubtless because the drawings are, after all, sketchy and incomplete.

The illustrations rarely present any pictures of the harnessing of oxen, but there can be no doubt of the significance of the development in regard to oxen. The notable feature is the appearance of

[108] LEFEBVRE DES NOËTTES, "*La force motrice animale*," pp. 96–98.

the multiple harness. Lefebvre des Noëttes shows that there is really no evidence of effective use in antiquity of several teams of oxen in file. The tendency was to arrange them abreast of each other, and in that form it was not possible to bring many teams together under circumstances of much practical use. The clumsy proposal for moving heavy weights by animal power that appears in the text of Vitruvius does not indicate much facility either in the application of animal power or in arrangements for handling large stones.[109] The development of the use of several teams of oxen in line must doubtless be associated with the multiple plough teams of the Germanic peoples. The heavy sod of the humid regions required a more elaborate plough than was in use in the Mediterranean countries. The simple, pointed plough was wholly inadequate and a plough with mold boards was developed at an early date. Hence the plough teams of eight oxen, the long furrow, the typical acre in the 1 to 10 proportion, and the field plots of the north which are so distinct from the square surveys of the Græco-Roman Mediterranean domains. The fact of the early use of multiple ox teams can hardly be doubted, but we are without detailed knowledge of the arrangement. There can hardly be much novelty in the citation of the eleventh-century description of the work on the church at "Conques" which involved the use of 26 teams of oxen in the transport of the bases and capitals of the columns.[110]

Improvements in the conditions of the use of animal power were also made by the provision of adequate protection for their feet. The iron horseshoe attached with nails appeared almost simultaneously in northwest Europe and in the Byzantine empire. There are drawings in miniatures, text references in the Strategon of the Emperor Leo (*c.* 900), and well-attested archeological finds. The evidence becomes more voluminous by the twelfth century.[111] Some of the finds are attributed to the eighth century; the miniatures are of the ninth century. The Byzantine evidence is not quite as early as the European evidence, but it is scarcely safe to make inferences from the differences of date in the evidence now known. The general coordination between the development of the harness and the horseshoes is rather striking. The new

[109] "Vitruvius," ed. Choisy, Vol. II. pp. 72–79.

[110] Mortet, "*Textes relatifs à l'histoire de l'architecture en France*," p. 105–106. Cited by, Lefebvre des Noëttes, "*La force motrice animale*," p. 97.

[111] Lefebvre des Noëttes, "*La force motrice animale*," pp. 98–100.

devices were fully established and widely diffused by the twelfth century.

IV

Bennett and Elton have brought out clearly for the first time the fact that the early history of water mills is characterized by the presence of two sharply distinguished types. Trustworthy materials are available for the establishment of the general distinction, but most of the evidence about water mills does not admit of any decisive establishment of the general history of the two types. Crucial elements in the chronology suggested by Bennett and Elton rest upon the thinnest possible inferences.

Water mills of some sort are mentioned in Greek sources in the first quarter of the last century before the Christian era. There is an epigram of Antipater containing vague references to the water mill.

"Cease your work ye maids, ye who labored at the mill. Sleep now, and let the birds sing to the ruddy morn. Ceres has commanded the water nymphs to perform your task; and these, obedient to her call, throw themselves on the wheel, force round the axle tree and so the heavy mill."[112]

The chief critical difficulty lies in the identification of the author, as there were three poets of that name who flourished at about that time. The epigram is presumed to antedate the more specific reference in Strabo's geography. Strabo says (Geog. xii. 3) that Mithradates, King of Pontus had a hydraulic machine established in a park at Cabira, at the time of his defeat by Pompey in 65 B.C. Most commentators presume this device to have been a water mill. The reference, therefore, leaves much to the imagination even if Strabo is correct in speaking of a hydraulic machine. To these passages must be added one from Pliny's Natural History (*c.* 75 A.D.) in which he says:

"In the greater part of Italy is used a roughened pestle, or wheels turned by water, and sometimes also they employ for the purpose the mill." [*Major pars Italiæ nudo utitur pilo, rotes etiam, quas aqua versat, obiter et mola.*[113]]

[112] BENNETT and ELTON, Vol. II, p. 6.

[113] PLINIUS SECUNDUS, "Naturalis Historiae," Libri XXXVIII, ed. MAYHOFF, Leipzig, 1882, Vol. III, p. 169; Book XVIII, Sec. 23. I am indebted to Prof. A. E. Monroe for the translation and for discussion of the texts. BENNETT and ELTON, Vol. II, p. 8, use an inferior text and give a dubious translation.

Bennett and Elton, using an inferior text, interpret this passage to mean that the water mill was in general use in the greater part of Italy, and though they admit that the passage is doubtful, they build the conclusion into their general chronology. Taking the three passages together they draw the following inferences: the mills mentioned by Pliny as being in general use (*c.* 75 A.D.) were different from the geared mill described by Vitruvius because Vitruvius states explicitly in that connection that he did not propose to describe devices that were commonly known; as the "Greek," or horizontal, type was thus in general use in Italy in the first century A.D. and as the geared mill was regarded as a novelty by Vitruvius, the mills described by Antipater and Strabo must have been of the simple type which is described as "Greek" or "Norse." This structure of inferences thus rests upon the thesis that Pliny declares these mills to be in *general* use throughout the greater part of Italy.

These inferences are not warranted by the best text, even if we assume that the present text of the passage contains no subsequent interpolations. Water mills and querns were in use in rural Italy in addition to the pestle and mortar, but there is no warrant in the text for the conclusion reached by Bennett and Elton:

"The Greek mill of Antipater . . . was in use about 160 years before, and probably by the time Pliny wrote had been adopted in the hilly regions of Italy by the rural population, who had up to then ground grain by hand."[114]

It is dangerous to assume that a particular passage in a classic author was part of the original text and the danger is especially great in the case of Pliny. Under these circumstances, the three passages can hardly be accepted as more than casual evidence of the early existence of water mills. The supposition that these mills were of the gearless type is mere conjecture; plausible, because we naturally presume that the simpler mechanism precedes the complex. At the same time, it should be recognized that an exclusively northern origin of the gearless horizontal mill is not impossible. Vitruvius does not imply that the geared mill was an invention of his own; it was merely a somewhat unusual mechanism that was particularly worthy of description. There is no decisive evidence that the water mill was at all common in Rome earlier than the fourth century.

[114] BENNETT and ELTON, Vol. II, p. 9.

In 398, Honorius and Arcadius issued an edict to protect the water supply used in driving the mills of the city.[115] As it is later established that these mills were largely located on the Janiculum, the reference of Prudentius to the mills of the Janiculum can be assumed to mean the water mills, and in that case the water mills had already become the chief reliance of the city.[116] A century later, Zeno forbade individual use of the public water supply for the driving of mills (485). The prohibition was reiterated by Theodoric. At the siege of Rome in 536, Belisarius found the city threatened by the cutting of the aqueducts and resorted to the expedient of erecting water mills on boats in the Tiber. In 550, Procopius speaks of the Janiculum as the place where are erected: " . . . all the mills; a large body of water being conveyed by timber structures, direct from the top of the hills, and the water falling down the slopes with considerable force."[117]

In 650, we hear of mill building inside the city by the Pope Honorius I. There can thus be little doubt of the continuity of the development of milling by water power in Rome after the late fourth century. As these mills must have been established prior to the edict of 398, the substantial origins must be carried considerably further back.

The development was not confined to Rome, for at the close of the fourth century there are references in Ausonius' poem on the Moselle and in the "De Re Rustica" of Palladius.[118] The latter advises the construction of water mills wherever there is sufficient water, and it is evident that the mill was thoroughly known. Thus, without being able to distinguish the types of mills, we can feel confident that the general introduction of mills may be identified with the fourth century. How much earlier their general use may have been we cannot say: evidence is scant and we have really only casual references that do not clearly indicate more than restricted use in relatively small areas. The references to mills outside of Rome are practically continuous from the fourth century. Furthermore, the evidence available affords especially

[115] BENNETT and ELTON, Vol. II, p. 41. Text and translation of the passage from the Theodosian code.

[116] BENNETT and ELTON, Vol. II, p. 39. "What quarter of the city can endure famine, the gradus being empty? or what, the motion of the mills of the Janiculum being stopped?"

[117] BENNETT and ELTON, Vol. II, p. 40.

[118] BENNETT and ELTON, Vol. II, p. 2; AUSONIUS (about 380 A.D.) "Mosella," line 362; PALLADIUS (about 371–395 A.D.) "De Re Rustica," Vol. I, p. 42.

strong indices of general use as our chief references to mills from the late fifth century to the ninth century come from the Teutonic codes. The dating of material in these codes is of course a matter of difficulty: in most instances large portions of the code were current as oral tradition before they were reduced to writing, nearly all of the more important codes passed through several editions. The Visigothic code was first reduced to writing in the latter part of the fifth century; the early form of the Salic law is commonly identified with the beginning of the sixth century; the Lombard code known as the edict of Rothar and the laws of the Alemanni are identified with the seventh century. Later editions of the older codes appear in the eighth century; a Welsh code also appeared at that date, and in the early ninth century come the laws of the Chamavarian Franks. Water mills appear in all these codes, and in all the text variants of the important Salic law. These references are supplemented by two references in the writings of Gregory of Tours and by a small number of charters of the seventh and eighth centuries.[119] The Polyptic of the Abbey of St. Germain enumerates 81 mills and 3 mill sites not at the moment occupied. The estates comprised 2,788 servile households and some free households not enumerated. The total population is estimated at 18,000 persons, which would indicate an average of 1 mill per 220 persons. Many of these mills are explicitly described as water mills or as located on streams which would leave little doubt of identification. The editors hold that the water mill was dominant though some use was still made of hand stones.[120] From this date the extension of the use of mills admits of little doubt, though references in charters are not abundant for another century or more.

None of these materials afford any clues whatsoever to the type of the mill, but the Irish code known as the "Senchus Mor" contains explicit description of the parts of a mill,

" . . . for the eight parts which constitute the mill: the spring, the mill-race, the land of the pond, the stone, the shaft, the supporting stone, the shaftstone, the paddle wheel, the axis, the hopper."[121]

[119] Bennett and Elton, Vol. II, p. 71; Beck, G. d. E., Vol. I, pp. 952–953.

[120] Lognon, A., "*Polyptique de l'Abbaye de St. Germain des Près de l'Abbè d'Irminon*," Vol. I, p. 108.

[121] "Ancient Laws of Ireland," Vol. I, p. 125; Bennett and Elton, Vol. II, p. 89.

These are the parts of the horizontal mill. The parts of the mechanism may be identified in the figures given above, and the failure to mention any geared wheels is of evident importance in a comprehensive enumeration. This is, therefore, the earliest reference to the horizontal, or "Greek" mill that can be dated with any certainty, and though the establishment of the date of the 'Senchus Mor" itself is not without difficulty the conclusions of the editors seem sound. The code purports to be the result of reducing oral custom to writing at the time of the conversion of Ireland to Christianity by St. Patrick. The laws were examined and all provisions contrary to Christianity were rejected: all other customs were reduced to writing and declared to be forever the law of the land. No judge (Brehon) should henceforth set aside or alter any article of the law. The circumstances of the writing are described in some detail, and all aspects of the account can be substantiated in other sources. The editors thus recognize the code as a fifth-century work composed between 438 and 441 A.D. The other primary text of early Irish law, the "Book of Aicill" is held to be at least contemporary with the "Senchus Mor," though this code purports to have been reduced to writing towards the close of the third century.[122]

The significance of this identification is not confined to the relatively early date, for the character of the relations of the parties using the mill throws important light upon the character of mills mentioned in the various Teutonic codes. There is a long passage in the "Book of Aicill" concerning responsibilities for accidents happening in a mill. Three principals appear; the mill owner, the millwright, and the grinder. In addition, fellow laborers, unprofitable fellow laborers, and idlers are mentioned. The mill and its visitors are thus comprehensively described. The damages are assessed according to the degree of responsibility. The first accident due to slipping of the stones imposes no liabilities unless owner or millwright were aware of the defects. Thereafter, liabilities are imposed on one or both according to the degree to which their negligence was involved. The circumstances recited show that the mill was provided by the owner for the use of others: that there was no professional miller; that each party came along to grind with or without assistance.[123] The mill would thus be private property, but would present the unusual circumstance of

[122] "Ancient Laws of Ireland," Vol. I, pp. xi, xxvii; Vol. III, p. clxii.

[123] "Ancient Laws of Ireland," Vol. III, pp. 281–283.

being free of access to all, with or without the presence of the owner, subject to customary arrangements for compensation.

The early Irish law of the mill thus presents a sharp contrast to the feudal law that ultimately developed with its impositions of obligations to use the lord's mill, carried even to the extent of a prohibition of the use of the quern. All of these special features of early Irish law appear in the provisions of the Teutonic codes, and, as Koehne points out, the striking feature is not the communal ownership formerly presumed to have existed, but this rather special kind of freedom of access to private property.[124] The absence of a professional miller and the intermittent use of the mill, point strongly toward the likelihood of the predominence of the horizontal or "Greek" mill throughout the period dominated by these rules. Even on the domains of the Abbey of St. Germain des Pres the mills seldom had millers in regular attendance. There is thus a very strong presumption that this type of mill was generally known in continental Europe and in portions of the British Isles at least as early as the beginning of the sixth century, and perhaps earlier. In that event, diffusion from restricted areas, whether Norse or Greek, must needs have occupied a considerable period. Any decisive item identifying this mill with Greece would go far towards completing the account of the early history of mills.

Bennett and Elton hold that the Roman type of mill "supplanted" the horizontal or Greek type about the eighth century,[125] but there is no indication of the inferences by which the conclusion is reached. By the twelfth century the Roman mill with its highly characteristic vertical wheel can be identified in the pictorial representations, and at that time the horizontal or Greek type leaves scarcely any trace in the illustrations, though it undoubtedly continued in use. Without additional sources of information we cannot date with more precision the displacement of the simpler by the more complex type.

The "Domesday Survey" is probably the most extensive enumeration of mills in this early period. A complete list of all the mills and their rentals is given by Bennett and Elton.[126] The striking feature is the wide range in rental values. One rental is cited at 3 pence and a substantial number yielded less than 1 shilling. Some

[124] Koehne, "*Das Recht der Mühlen bis zum Ende der Karolingerzeit*, p. 71.
[125] Bennett and Elton, Vol. II, p. 10.
[126] Bennett and Elton, Vol. II, pp. 130–180, and p. 108.

may be found rated as high as £3. Even casual study of the list leaves one with a vivid sense of the number of small mills and the predominance of mills rated at less than £1. The list could hardly be accepted as evidence of the predominance of the horizontal mill, as it is impossible to say how small some of the "Roman" mills might be.

The development of the larger mills and of a permanent occupational group of millers was the outcome of two general changes. Some centralization took place in the administration of the great estates and large mills were built which were utilized more or less voluntarily by the tenants of the estates. Some of the feudatories set up claims to exclusive jurisdiction over milling so that they attempted both to limit the number of mills that might be set up and to enforce an obligation upon all tenants to grind at the lord's mill. In neither attempt were they wholly successful. Feudal law could not entirely submerge the old doctrine that the owner of land might erect a mill if no injury were done to the land of another. Neighboring owners could not be restrained from building mills, and in practice it was difficult to enforce the obligation of tenants to grind at the lord's mill. These new tendencies appear in a small way early in the ninth century, being illustrated notably by the statute of Adalhard, Abbot of Corbie, first issued in 822 but now available only in revised texts: one revision being made between 822 and 844, and others later in the ninth century and even at the beginning of the following century. In these we hear of large mills with six pairs of stones, of professional millers, and of the obligations of the millers to feed poultry and pigs with the waste from the mill.[127] This is the kind of enterprise that milling developed into under the influence of the centralized estate administration that became increasingly common. The mill thus became an important kind of property; special provisions of feudal law were developed to protect it; more attention was given such items in charters and deeds. The new type of enterprise thus created new classes of evidence which become increasingly common after the ninth century. In Germany and France, these new legal arrangements were stabilized in the course of the tenth and eleventh centuries.[128] The obligation to grind at the lord's mill was not, how-

[127] LEVILLAIN, "*Les statuts d'Adalhard, Le Moyen Age*," Vol. XIII, pp. 352, 357, 358, 383, 384.

[128] KOEHNE, "*Die Mühle im Rechte der Völker*, *B. G. T. I.*, Vol. V, pp. 36–37; DELAMARE, N. "*Traité de la Police*," Vol. II, p. 799.

ever, generally recognized: Delamare says that it was admitted by only 31 customs of 290 recognized as valid sources of law in France; and only 10 customs treat it as a feudal right. In England, some declare that the milling obligations of tenants were established prior to the conquest, but there is no evidence in "Domesday" of any general obligation to grind at the lord's mill, nor much indication that the lords objected to the building of mills by tenants for their own use or for revenue.[129] After the conquest, the feudal rights developed in England on a considerable scale and seem to have been extended to greater extremes than in France and Germany. Beginning in the twelfth century, individual lords attempted to enforce their monopoly even against the use of hand mills (querns). In 1274, St. Albans Abbey at Cirencester began a contest with the people of the town requiring them to give up their querns. The right was enforced only by the application of considerable pressure and a violent conflict broke out 50 years later. The abbey was attacked and permission to use querns was secured. After an interval of 6 or 7 years, the Abbot made a descent upon the town, searched out all the querns and broke them up on the spot save for a modest number that were carried to the abbey to pave the parlor floor.[130] The contest was continued without success by the townspeople. A number of similar instances are given by Bennett and Elton and their list is by no means exhaustive. Some feudal rights were extinguished by purchase, but in England a number of cases survived into the second half of the nineteenth century, when they were extinguished by purchase or allowed to lapse.

The development of towns also led to a considerable increase in the scale of milling, and no doubt these urban conditions are more largely reflected in our pictures than the conditions of the remote rural villages.[131] Mills were built in close association with bridges and on many of the European streams floating mills were erected after the manner of the mills built by Belisarius during the siege of Rome in 536. The renaissance of town life can hardly have proceeded far enough to exhibit conspicuous economic effects earlier than the eleventh century, and thus there are various grounds for attributing the transition in milling to the eleventh century rather than to the earlier date suggested by Bennett and Elton.

[129] Bennett and Elton, Vol. II, p. 122–123.
[130] Bennett and Elton, Vol. II, p. 215–216.
[131] Espinas, "*La Vie Urbaine à Douai,*" Vol. II, pp. 403 *ff.*

V

Apart from the isolated reference in Ausonius to a water-driven saw to cut marble, the earliest known applications of water power outside the field of grinding grain are to be found in the textile industry. References to fulling mills driven by water power begin to appear in the second half of the twelfth century and as they are fairly continuous as well as fairly numerous there can be scarcely any doubt of the established use of some device. References to mills for crushing woad and tan bark at the same date suggest a form of mill that might be equally well applied to any light task of stamping, crushing, or fulling.[132] The earliest of any of the references is to a mill for crushing oak bark noted in a charter of 1154. The references to fulling mills begin in 1168, continuing 1182, 1191, 1208, 1256, 1289, 1307, 1309, 1313, 1334, 1385, 1397, 1400, 1408. Tan-bark mills are cited for 1154, 1217, 1228, 1231, 1279. Woad mills are cited only in the late fourteenth century. Without measurably contemporaneous illustrations we cannot profitably speculate as to the nature of the mechanism, and the earliest drawing of any such apparatus is the fifteenth century sketch of the Hussite engineer (*c.* 1430) which is described by Beck as a stamping mill for use in crushing ore.[133] This general type of apparatus was one of the three characteristic forms of the fulling mill in use in the eighteenth century. The significance of these references is only partially dependent upon an exact identification of the apparatus, for we can be practically certain that these devices were in any event part of the general family of trip hammers. By an appropriate arrangement one or more hammers were rigged up so as to be lifted by a cam on a revolving cylinder or wheel: as the cam passed by the end of the hammer or some projection, the hammer was released and it fell of its own weight. Such devices play an important part in a considerable series of trades. The fulling mill and these bark crushers are merely light-duty machines of an important and extensive family.

The sawmill presented an intrinsically more difficult problem, and though we possess no details it is almost certain that contribu-

[132] The references known are citations in the glossary of Ducange, so that we need not assume that they represent as comprehensive a list of cases as is commonly true of the lists of references to mechanical apparatus in classical writers. The passages appear under the word, "*Molendinum.*"

[133] Beck, G. M. B., p. 280, Fig. 325.

tions were made to this apparatus by a long series of inventors. We cannot attach much importance to the isolated reference to a stone saw run by water power on a tributary of the Moselle at the close of the fourth century.[134] The fact is doubtless as stated, but without more references it seems scarce likely that it was of much general significance. Some note should appear of other cases if the practice were at all common. After that date, we hear nothing of power saws, until we come to the "Album" of Villard de Honnecourt, an ecclesiastical architect of the thirteenth century. Here we find two sketches of saws, one of which, at least, is supposed to be driven by water power. The sketch is reproduced in Fig. 46.[135]

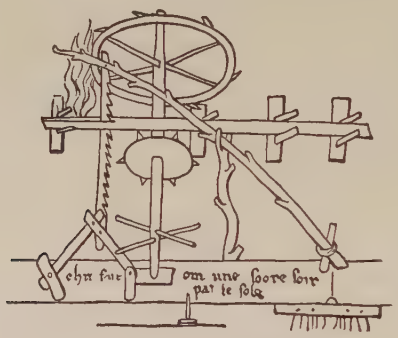


FIG. 46.—Saw mill, thirteenth century.

The upper end of the saw is fixed to a light pole, the lower end is fastened to moveable cross-pieces which are periodically depressed by the short bars protruding from the axle of the water wheel. The down stroke of these bars brings the saw down; the return motion being produced by the elasticity of the pole. There is no mechanism for moving the log or holding it against the saw. Nothing could be more rudimentary, and as this is the earliest reference to a power saw, one wonders if the sketch is a record of apparatus actually used or a suggestion of something that might be tried out. Charter references to sawmills begin early in the fourteenth century with an undated charter of Phillipe le Bel. Other references are available for various points in France for the dates 1376, 1391, 1393, 1400, 1415.[136] In Germany, sawmills

[134] AUSONIUS, "*Mosella*," line 362.

[135] *B. G. T. I.*, Vol. X, p. 178, Fig. 5.

[136] DUCANGE, *Glossarium*, s. v., *Molendinum de planchia, Molendinum resseguæ, Ressega, and Ressegare.*

are mentioned at Augsburg in 1337 and 1389. There were sawmills established on the island of Madeira in 1420; at Breslau in 1427. Thereafter, there can be no doubt of the continuous application of water power to sawmills in various localities.[137]

There is also evidence of some application of water power to grindstones for polishing metal and sharpening edge tools. References are rare, and it is commonly held that the metal trades were dominated by hand tools until at least the fifteenth century. Espinas refers, however, to a water mill established at Douai in 1313 in connection with edged-tool making, and Ducanage cites a charter of 1390.[138]

The application of gearing to mills turned by horses or by men or by the wind, and the extension of generalized power to other tasks than turning millstones mark the beginnings of the generalized application of power. Some facility had developed in the utilization of various sources of power, and before 1400 at least modest successes had been achieved with simple apparatus in several fields outside the flour-milling industry. Mechanicians were beginning to think of producing and transmitting power, but their efforts were crude and restricted within narrow limits.

[137] Poppe, "*Geschichte der Technologie*," Vol. II, pp. 34–36.

[138] Espinas, "*La Vie Urbaine à Douai*," Vol. II, pp. 403–404; Ducange, Glossarium, s. v., *Molendinum ad cutella*.

Chapter VI

WATER CLOCKS AND MECHANICAL CLOCKS: 16 B.C.–1500 A.D.

I

The early history of power machinery centers around the development of the geared grinding mill. The refinement of mechanical design and the development of complete facility in the use of geared wheels centers around the invention and perfection of mechanical clocks and watches. The history of the clock, too, was sufficiently interesting to contemporaries to create more abundant records than we possess of other mechanical devices of the Middle Ages, so that even if the primary development of fundamental principles of applied mechanics was not largely based upon the problems of the clock, the history of clocks would still remain of outstanding significance because it is more adequately documented than any other phase of mechanical development in the thirteenth, fourteenth, and fifteenth centuries. Our primary sources are thirteenth-century treatises on water clocks in Arabic and Spanish, extant movements of mechanical clocks dating back to the beginning of the fourteenth century, sufficient contemporary text description of some of the early clocks to identify the original design of the movement. We are thus only in part dependent upon early drawings and text descriptions. We have adequate means of appreciating the precise technical competency of the period.

Although the history of clocks has been a subject of interest for more than a century and a half, the course of events prior to 1300 has long been completely misunderstood and the older views still persist wholly or in part even in notable recent books[139] despite the decisive achievements of Sheridan, Fremont, Diels, and Wiedemann. Most of the historical difficulties have grown out of confusion between water clocks and mechanical clocks and

[139] MILHAM, "Time and Timekeepers"; WINS, "*L'Horloge à travers les Ages*"; BOLTON, "Time Measurement."

misunderstanding of the relation of the two types to each other. The water clock appeared in ancient Egypt at an early date; it was developed significantly by the Greeks and in the forms then achieved persisted through the early Christian period with little essential change. Supplemented by sand glasses and sundials, the water clocks played a notable part in keeping time down to the close of the thirteenth century, and even after the appearance of the mechanical clock the older device continued in use until the eighteenth century though considerably changed in the details of its construction. The use of geared wheels was ultimately taken over from the mechanical clock and the construction considerably simplified. Although such clocks were less accurate than the mechanical clocks, they were so much cheaper and so much less difficult to keep in repair that they were an important factor in the generalization of the use of clocks. In the seventeenth century they were made to resemble the mechanical clocks in all their external details, including the striking apparatus.[140] These elements in the history of clocks were hopelessly obscured by Perrault's illustrations of the text of Vitruvius. The water clock there described was depicted as a sixteenth-century mechanism with gearing. The actual relationship between the two types of clock was reversed. The matter was further complicated by the misinterpretation of the term "Horologium" by Ducange. He failed to realize that the word was regularly applied to the water clock in the early Christian period and thus a considerable number of references to water clocks and their development were taken to refer to early forms of the mechanical clock whose origins were thus carried back to the ninth and tenth centuries. Despite a measure of skepticism, these versions of the early history of the clock still persist, although the evidence against them has latterly become decisive.

II

The simple water clocks for domestic use involved little or no mechanism. Simple attachments would suffice to sound the hours by the dropping of a ball into a bronze gong or by the blowing of a reed trumpet. The water clock presented a mechanical problem only when it was associated with devices to actuate puppets at designated hours or with devices to display some of the phases of

[140] MARTINELLI, D. "*Traité des Horloges élémentaires*," 1663, in OZANAM, "*Recreations Mathématiques*," Vol. III, pp. 307–308.

the movements of sun, moon, and stars. Vitruvius implies that this development of the monumental clock had already begun in his day, but we have no references to any specific clocks of large size earlier than the clock at Gaza described by Procopius in the sixth century.[141] The text is not very satisfactory as the description is confined to the external features of the apparatus. The clock was contained in a small temple-like building in the market place, the facade of the clock being thoroughly protected by the portico. A Medusa head decorated the tympanum of the facade. Beneath the cornice were two rows of doors: twelve plain doors for the hours of the night; twelve decorated double doors for the hours of the day. In front of the doors for the hours of the day stood a figure of the sun god which moved from left to right to mark the passing of time. On the level of the temple floor stood three figures of Hercules in decorative settings. At each hour of the day one of the doors of the hours opened and one of the labors of Hercules was displayed by figures. The eyes of Medusa moved. One of the figures of Hercules below struck the number of the hours; counting from one to six for the morning and again from one to six for the afternoon. The hours of the night were indicated by the opening of the appropriate doors, which were illuminated by lamps. Some other motions were also produced which need not be described here, for it is sufficiently evident that the monumental clock represents a combination of the water clock in its simpler forms with the puppet theatre as described by Hero. This composition of mechanical effects remained popular throughout the history of the water clock and one of the chief legacies of the older to the newer instrument was this combination of the clock and the mechanical puppet show.

We have references to ten or twelve monumental water clocks that were built prior to 1250: most of them were the work of Moslem mechanicians, but some were sent to Christian monarchs as presents, and apparently some were built in Latin Europe.[142] Fortunately, minute descriptions of some of these clocks are preserved in the Arabic treatises of Gazari and Ridwan which were composed about the beginning of the thirteenth century. These treatises show decisively that the technique of the water-clock makers was essentially based upon the technique of the automatic puppet theater. Motions were produced by weights linked up by cords with rollers and pulleys. In the water clock the control of

[141] DIELS, "*Ueber die von Procop beschriebene Kunstuhr von Gaza.*"
[142] WIEDEMANN, pp. 36–38.

motion was secured by the motion of a float suspended in the basin that was filled or emptied by the regulating mechanism. In these devices no use is made of gears.

The general features of the clock of Gazari are shown in Fig. 47.[143] The facade is about 12 feet high. The arch at the top of the

FIG. 47.—The water clock of Gazari: facade.

figure contains a moveable strip bearing the twelve signs of the zodiac. The discs in the slots just below, which represent, respectively, the sun and the moon, rise and set according to the season in the proper sign of the zodiac. There are then two rows of twelve doors T' T''; in the upper row, the door opens at the end of the

[143] WIEDEMANN, p. 63.

hour and a figure comes out; in the lower row, the door is turned so that its color is changed. An indicator *D*, in the shape of a cres-

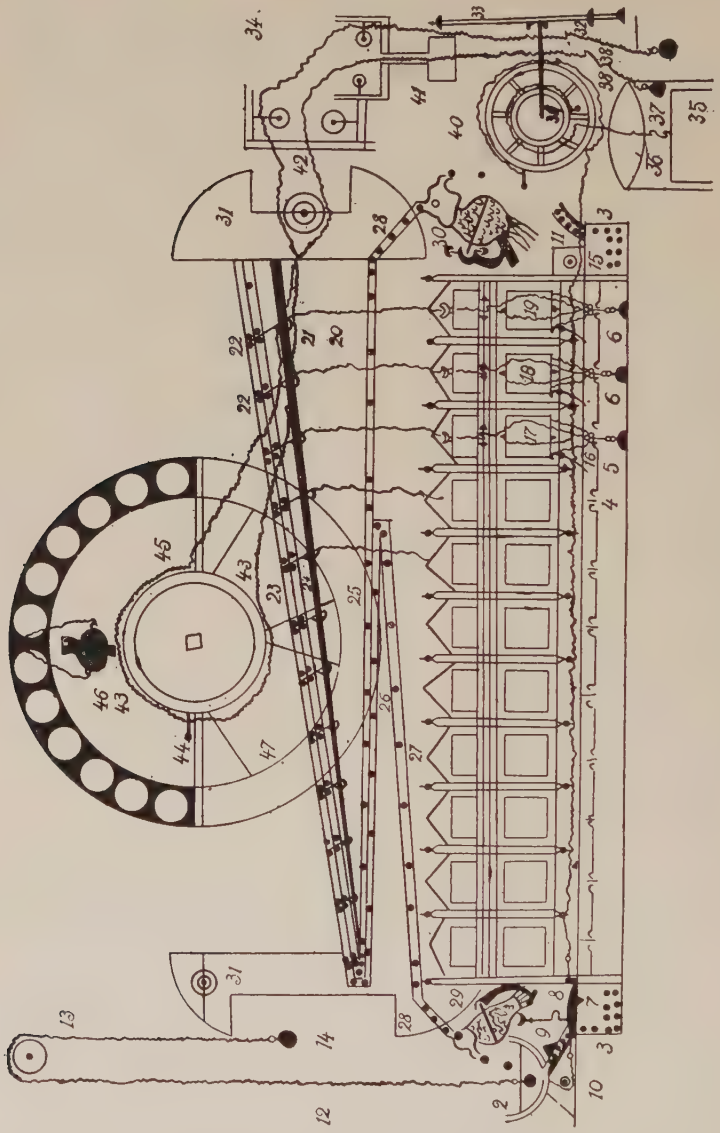


Fig. 48.—Water clock of Ridwan: Damascus.

cent, moves along a little track so that the indicator passes before the lower row of doors. At the end of each hour, the birds V_1, V_2

in the niches bend forward and drop a ball into the bronze vessels B_1, B_2 in front of them. At the sixth, ninth, and twelfth hours, the Trumpeters M_3, M_4 blow their trumpets; the drummers M_1, M_2 beat their drums, and the cymbalist clashes his cymbals. At night, at the beginning of the first hour a tiny light appears in the first of the twelve globes *SS*. The light increases in volume until by the end of the hour the whole globe is lighted. The same procedure takes place successively in each globe. At the sixth, ninth, and twelfth hours the musicians perform.

The most representative single drawing of the works of such a clock appears in the treatise of Ridwan describing the clock at Damascus, built originally by his father in the middle of the twelfth century and restored by him at the beginning of the thirteenth century. The original illustration is reproduced in Fig. 48.[144] Without minute discussion of details it will be readily apparent that the mechanism contains no geared wheels. Movement is communicated from the float 35 by means of cords passed around various rollers and pulleys with various counterpoised weights.

The smaller clocks did not differ from the large ones in the principles of construction but only in the degree of complexity. The treatise of Gazari contains descriptions of nine water clocks and one clock controlled by a wax candle. There are "Five Books on Clocks" in the "*Libros del Saber de Astronomia*" prepared under the direction of Alfonso X of Castile (*c.* 1256).[145] There are complete directions for the construction and use of water clocks and for the construction of the candle clock and a device based upon the control of a falling weight by the resistance created by the passage of mercury from one compartment to another of a closed drum through small apertures; the basic principle of the sixteenth- and seventeenth-century water clocks. In none of this material is there any indication of the kinds of gears that appear in Hero's hodometer or in the mechanical wheel clock. Unless specific evidence is produced there is no warrant for presuming that there was a close relation between the mechanism of the early water clocks and the geared clock.

It was presumed by Ducange that the liturgical requirements of the monastic houses created a demand for clocks that led to the

[144] Wiedemann, p. 248, Fig. 132.

[145] *Libros del Saber de Astronomia del Rey D. Alfonso X de Castilla.* Manuel Rico y Sinobas, Madrid, 1866, Vol. IV, pp. 24–107.

development of the geared clock as early as the ninth and tenth centuries. The descriptions of the horological work of Pacificus, Archdeacon of Verona (*c.* 850) and of Gerbert (later Pope Sylvester II) are not sufficiently explicit to warrant the interpretation sometimes placed on them. The mortuary inscription of Pacificus merely says that he first made a night clock (*horologium nocturnum*).[146] Gerbert is said to have made a clock for the monastery at Magdeburg which kept time night and day. William of Malmesbury says it was made according to mechanical principles (*horologium arte mechanica compositum*).[147] The clock was adjusted at night by taking observations of the pole star, a practice referred to in the works of Alfonso X of Castile in the "Libros del Saber de Astronomia." There are extensive references in the "Rule of the Cistercians" to the duties of the keeper of the clock, but recent discoveries have shown that these relate to the care of a water clock. Fragments of slate were found among the ruins of the Abbey of Villers in 1894 which proved to be the rough notes made by the keeper of the clock with reference to his duties. By means of internal evidence these can be dated as of the years 1267–1268, and careful study has made it possible to build up a complete commentary upon the functions of the clock keeper as given in the general text of the rules. The rough notes preserved on the slates refer specifically to filling the reservoirs of the clock with water so that there can be no doubt of the general character of the instrument in use at the abbey. All the terms formerly held to refer to mechanical clocks occur in the notes and thus it becomes evident that the Latin terminology was transferred bodily from the water clock to the mechanical clock; both instruments bore the same name and their care was described in similar terms.[148] We must assume that Pacificus and Gerbert were concerned with the introduction of water clocks into the monastic houses.

[146] Ughelli, Fernando, "*Italia Sacra*," Vol. V, p. 609.

[147] Wilhelmi Monachi Malmesbiriensis, "*De Gestis Regum Anglorum*," Lib. Vol. II. Sec. 168, ed. Stubbs, 1887; Vol. II, p. 196. The passage in Ditmarus, "*Chronicon*," Lib. VII. Sec. 40 (VI, 61) is still less explicit.

[148] Sheridan, Paul, "*Les Inscriptions sur Ardoise de l'Abbaye de Villers*, *Annales de la Société d'Archeologie de Bruxelles*, Vol. X, pp. 203–215, 404–451, 1896. The full text of the essential passages of the customs of the Cistercians is given and discussed in detail.

III

The primary mechanical elements of the clock with geared wheels had long been known. The use of weights as a driving mechanism extends far back into the pre-Christian period. The use of gears begins in a small way in the pre-Christian period and their use was widely extended in the milling industry. The use of such elements for the measurement of time was long an impossibility because there was no means of controlling the force of the falling weight. Without some form of escapement, the falling weight would not measure time because it would move at an accelerating rate.

The earliest known form of an escapement appears in a primitive device in the Album of Villard de Honnecourt. The apparatus is so naïve and presents so little specific resemblance to any successful escapement that the nature of the device was not perceived until two generations had studied the published plates of the manuscript. The original drawing and a supplementary figure are reproduced in Fig. 49.[149] The drawing carries the legend "*Par chu fait om un angle tenir son doit ades vers le soleil.*" (By this means an angel points its finger toward the sun.) The apparatus thus served a purpose somewhat related to time keeping, but without being subjected to any minute requirements of accuracy. The image mounted on the point at the right must make about a half turn in the course of the daylight hours.

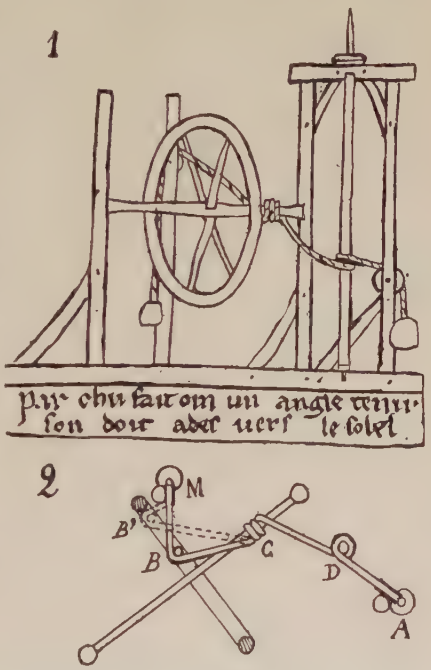


FIG. 49.—Escapement by Villard de Honnecourt, about 1250.

[149] *Comptes Rendus de l'Académie des Sciences*, Vol. 161, p. 691, 1915.

The rope with weights at each end is passed around the spindle carrying the image, around the shaft of the wheel, back of one of the spokes of the wheel and then forward over the pulley on the post that is presumed to stand at the right of a wheel at right angles to the plane of the paper. One weight is presumably heavier than the other, according to the direction of the movement to be produced: apparently the weight at the left is intended to be the heavier. If the spokes of the wheel are in such a position that the rope is bent as in position *B* in Fig. 49, there is not enough resistance to prevent the weight at *M* from falling. The rope unwinds, turns the spindle of the image and the axle of the wheel until the spoke of the wheel is brought into position B^1, pressing the rope firmly against the rim of the wheel and the post to which the pulley is attached. The motion of the wheel is arrested. It recoils, but the weights must be presumed to be adjusted so as not to produce any substantial reversed motion in the image. The fall of the weight would be periodically checked and released. The essential elements of an escapement motion are thus embodied in the crude device which can be pretty certainly attributed to the middle of the thirteenth century. Another plate in the album[150] depicts a clock tower, so the architect must have been fully abreast of his time in this as in other aspects of mechanical knowledge.

Until 1344, there is no clock movement of whose general characteristics we can be wholly certain. There are references to fourteen large clocks for external towers or for some interior position in a building, and there is one reference to a clock with weights and wheels said to have belonged to Phillipe le Bel of France. With one possible exception, there is little reason to suppose that any of these mechanisms were water clocks; but on the other hand, there is no means of knowing to what extent they were complete clock mechanisms at the dates assigned to them. The records of the Cathedral at St. Paul's are probably representative of the actual process of development. There are references in the account rolls which indicate the presence of a clock keeper as early as 1286. In 1298, stated sums were spent for making "jacks" to strike the hours. In 1344, a contract was made for the preparation and placing of a dial.[151] This record thus suggests the gradual composition of a complete clock. At first without any wholly adequate

[150] Sheet 6 verso, of the original. The design is presumed to be a copy of a tower seen by Villard de Honnecourt.

[151] MILHAM, p. 62.

striking apparatus, but finally developed into a full-fledged clock. Another kind of device is apparently involved in the gift of the Sultan of Egypt to the Emperor Frederick II in 1232. It was said to resemble . . . "internally a celestial globe in which sun, moon, and planets moved being impelled by weights and wheels so that they pointed out the hour, day and night with certainty."[152] This was a kind of orrery, therefore, which incidentally gave a version of the time, but despite the text one may doubt the achievement of accuracy or even the primacy of the purpose to tell time. Basserman-Jordan assumes that it was a water clock.

The known list of mechanical "clocks" prior to 1344 is as follows:

1232	"Clock" (orrery) sent by the Sultan to Frederick II
1286	"Clock" at St. Paul's Cathedral, London
1288	In the palace yard at Westminster
1292	At Canterbury Cathedral
1299 to 1300	Tower clock at the Royal Palace: Paris. Said to have been made by Pierre Pipelart
c. 1300	Domestic clock said to have belonged to Phillipe le Bel
1314	Caen
1318	Exeter Cathedral
1320	Peterborough Cathedral
1320	Wimbourne Minster
1323	Norwich Cathedral
1324	Beauvais Cathedral
1326	Monastery at St. Albans
1332	Courtrai
1335	Gladstonbury Abbey
1336	Asso Visconti, at Milan
1340	Exeter, St. Mary of Ottery
1340	Monastery of Cluny (*sic*)

The clock at Caen is supposed by Wins to have been a water clock and it must be confessed that the references are too vague to admit of any satisfactory identification of the character of the mechanism. The clock at the monastery of St. Albans is said to have had neither regulator nor escapement, so that it was rather a device for producing motions of the sun, moon, and planets than a time keeper. The clock at Peterborough Cathedral has survived and though restored in 1836 is still presumed to represent its early condition, though it is clearly impossible to know what changes were made in the early history of the mechanism. The clock had no dial so that its function consisted in striking the hours.

[152] Milham, p. 62; without authority.

Thomas Young, a lecturer on physics at the beginning of the nineteenth century, presumed that these early English clocks were regulated by a "fly," or fan. The fly has been used in the striking train of clocks since the early fourteenth century. The resistance of the fan to the air checks the motion of the weight and the principle is not without mechanical merit. The supposition that it was the sole regulator of the early English clocks is, however, an inference that is not supported by any specific evidence.[153]

This long series of clocks affords no really decisive evidence of any of the primary details of the mechanisms. There is no ground for doubting the significance of the achievement accomplished during the period 1275–1340, and the activity of work in various centers indicates much. Though many clocks were made in England, some foreign workmen were involved. Developments in Germany and in Italy in the years that follow suggest the existence of work not recorded. We must thus presume that work was being done on the clock in at least four widely separated regions; certainly in England, France, Switzerland, and Italy; and probably in Germany.

IV

There is no decisive evidence of the perfection of the foliot balance and verge escapement before 1348. The movement of the old clock at Dover Castle is preserved in the South Kensington Museum; it bears the date 1348, and there seems to be no grounds for supposing that the extant works do not represent substantially their original condition. The mechanism is somewhat simpler than the de Vick clock of 1369–1370 and it is likely that the Dover Castle clock is a trustworthy sample of early work, though it is by no means certain that it is the earliest complete mechanical clock movement.

The clock is said to be the work of Swiss mechanicians. Like most early clocks it carried only the hour hand. It struck the hours, but had no marionnette show. The works are set in an iron frame 28 by 20 inches. The wheel work is reduced to a minimum. "In the present state of the clock the 'scape wheel turns once in about 4 minutes which causes the great wheel to rotate once in about 55 minutes. No doubt originally it rotated

[153] YOUNG, THOMAS, A course of lectures on natural philosophy and the mechanic arts, London. Vol. I, pp. 189–190, 1807; BOLTON, p. 59; BERTHOUD, Vol. I, pp. 56–57.

once an hour. There may have been some gearing between the great wheel arbor and a hand, but if so it is now missing. The balance bar . . . is about 32 inches long and takes 7 or 8 seconds to perform one complete oscillation to and fro. The arc of oscillation seems to vary periodically in the course of an hour from 50 to 70 degrees and back again, the average swing being about 60 degrees. It is now impossible to say whether this has always been so, or whether it is the result of old age. It would of course make the clock a bad time keeper over shorter periods, say of an hour or so, but doubtless matters would average themselves out fairly well in the course of a day. There is a remarkable steadiness and absence of jerk in the oscillations of the balance, and the recoil in the mechanism while the bar is being brought to rest is less than might be expected, but the work expended must be considerable . . . There are many marks of careful design about this old machine which would not disgrace a modern drawing office. The particulars would hardly appeal to the general reader, but it is refinements of this kind rather than the appearance of the machine which impress the mechanician. To those who have the training to perceive it, there is in these early clocks evidence of a state of knowledge far in advance of anything to be gathered from the general histories."[154]

This description is especially important because of its careful appraisal of the probable efficiency of the clock. Milham takes the present performance of this old movement as a representative and fair index of its original performance, he concludes, therefore, that the clock would lose 2 hours in 24, and without further evidence this rather harsh judgment is generalized for all the early clocks. Bolton's view seems more in accord with probability. With sun dials and water clocks already available a mechanism that lost 2 hours a day would scarcely be worth while, but a measure of irregularity over short intervals of time would have been of no great consequence in a period in which people thought in terms of hours and major fractions. The balance and escapement are intrinsically sound in design and remained in use with little change for five centuries so that large coefficients of net error can hardly be in keeping with the known circumstances of competition between mechanical clocks, sun dials, and water clocks. The general persistence of water clocks to the seventeenth century, probably indicates that the mechanical clock without the pendu-

[154] Bolton, pp. 61–63; with photograph.

lum left much to be desired, but one can hardly reconcile the steady increase in the use of mechanical clocks with the notion that they were significantly less reliable than water clocks.

In addition to the mechanical clocks concerned primarily with striking hours and keeping time, various early mechanisms are known which represented the primary movements of sun, moon, and planets. The clock at St. Albans (1326) had features of this type and also the clock at Gladstonbury Abbey (1335). The dates and original condition of both of these clocks are somewhat in doubt. Although the general conception was hardly new and our knowledge of its mechanism is somewhat defective, special historical importance must be ascribed to the clock made by James (or John) Dondi at Padua, in 1344. The mechanical character of the instrument is fairly well certified and it seems to have exerted a great influece upon the development of clock building in Italy and southern Germany in the generation that followed. One must infer that its completion represented some substantial advance in the mastery of the general problems of construction. The most substantial contemporary or near contemporary reference is contained in the "Dream of the Old Pilgrim," by Philippe de Mezières (1327–1405).

"Be it known that there is in Italy in the city of Padua a man distinguished in the three sciences of philosophy, medicine, and astronomy. His surname is lost, and he is called John of the Clocks. He lives with the Count of Vertus from whom he has a pension of about 2,000 florins per year. This Master John of the Clocks has done notable work in his time in all three sciences, which is indicated by his reputation among the clergy of Italy, Germany, and Hungary. Among these works he made an instrument which is called the Sphere or Celestial Clock. This shows all the movements of the signs of the zodiac and of the planets with their cycles and epicycles . . . On a given night one sees clearly in what sign and at what altitude the planets and stars may be found. This sphere is made so ingeniously that despite the number of wheels which cannot be counted without taking the instrument to pieces, all the motions are governed by a single weight. This is such a great marvel that the august astronomers of distant places come with great respect to see Master John and the work of his hands . . . With his own hands, he forged the clock from bronze and copper without the aid of any other person, and for

16 years he did no other work, as the writer of this book has been informed by one who was a great friend of Master John."[155]

The list of known clocks built in the next 25 years is an index of the influence of Dondi's work in exciting the emulation of other towns.

Clocks were completed at the following dates in the towns given:

1344	Padua	1359	Siena
1348	Dover Castle	1362	Ferrara
1350	Pavia	1363	Fribourg in Bresgau
c. 1350	Douai	1364	Augsburg
1352	Strassburg	1367	Valenciennes
1353	Genoa	1368	Chartres
1354	Florence	(1359)	
1356	Bologna	1368	Breslau
1356–1361	Nürnberg	1368	Westminster (second clock)
1358	Tlemcen	*c.* 1370	Colmar
1358	Ratisbonne	1370	de Vick's clock at the Royal Palace, Paris

Six clocks were thus made in Italy and seven in Germany, and though we have no direct evidence the interest shown seems to have been created in no small measure by Dondi's effort.

V

In view of the number of clocks that were built in France it is strange that Charles V should have summoned a German to Paris when plans were laid for the making of a new clock for the palace. The project suggests that substantial improvements had taken place since the clock of Pipelart was installed in 1300. At all events, a German, Heinrich von Wick (the French form Henri de Vick is invariably used) was installed at the court about 1364 to make a clock which was completed about 1370 and installed in the tower of what is now the Palais de Justice. The present architectural setting was built in the sixteenth century, but the original movement suffered little change until the late eighteenth century. Happily, however, careful drawings were made of the clock in its original condition by Julian Le Roy, one of the most noted clock and watch makers of his day, so that while the movement no longer survives in its original condition we have as accurate knowledge of it as if the movement itself were available as in the case of

[155] Dubois, "*Histoire de l'horlogerie*," pp. 67–68; citing text from a Ms. in the Bibliothéque Nationale.

the Dover Castle clock. In a poem by Froissart we have further testimony to the fact that the eighteenth-century movement represents faithfully the original condition of the clock. The "Dittié d'Amour" called "Li orloge amoureus" was composed about 1368 if a brief reference in the Chronicles may be trusted. The poem is, in any case, closely contemporary with the building of de Vick's clock. In view of Froissart's contacts with the court, it may well have served as basis of the poem, which certainly affords striking evidence of horological terminology and of the primary mechanical features of the clocks of the time.[156]

The building of de Vick's clock thus properly brings the early history of clocks to a close, for from this point there can be no possible doubt of the complete mastery of all the primary principles, and prior to this date we cannot be wholly certain that some features of the movement were not added subsequent to the first construction of the clock. De Vick thus cannot be regarded as the inventor of the foliot balance and the crown wheel, but merely as the maker of a clock which is of unusual historical significance. As the instrument is certainly a more highly developed piece of workmanship than the earlier movements that have survived, we may presume that the Paris clock embodies some measurable advance, but the improvements may be matters of refinement in design rather than innovations.

The going train of the clock is shown in Fig. 50.[157]

"Round the wooden barrel *A*, which is about a foot in diameter, is coiled a rope attached to a weight *B*. The barrel is secured to a large toothed wheel *C*, which engages with a pinion *D*, the arbor of which is squared to receive the winding handle. The weight, it may be remarked, weighed 500 pounds, or close on a quarter of a ton, and fell 32 feet in 24 hours. This, however, was far exceeded by the striking weight, which approached three-quarters of a ton. These immense weights were required partly by the rough workmanship of the mechanism, a feature which is not evident from the present drawings, . . . All the parts of these clocks were evidently made on the anvil by a blacksmith. The friction between the working parts must have been enormous. The great weight is also in part due to the type of escapement used and also to the size of the wheels. Some of the wheels in the Wells clock look to be 3 feet

[156] Oeuvres de Froissart, "Poesies," ed. A. M. SCHELER, Bruxelles. Vol. I, pp. 53–86; Vol. II, pp. 201–220, 347–366, 599–614, 1870.

[157] BOLTON, Plate II, facing p. 57.

in diameter, and the size of those in De Vic's (*sic*) clock can be judged from the diameter of the barrel already given.

"The barrel and the winding wheel *C* are mounted freely on the arbor of the great wheel, or first wheel *E*, with which the barrel is connected by a pawl *F* and ratchet-wheel *G*. It is not necessary to

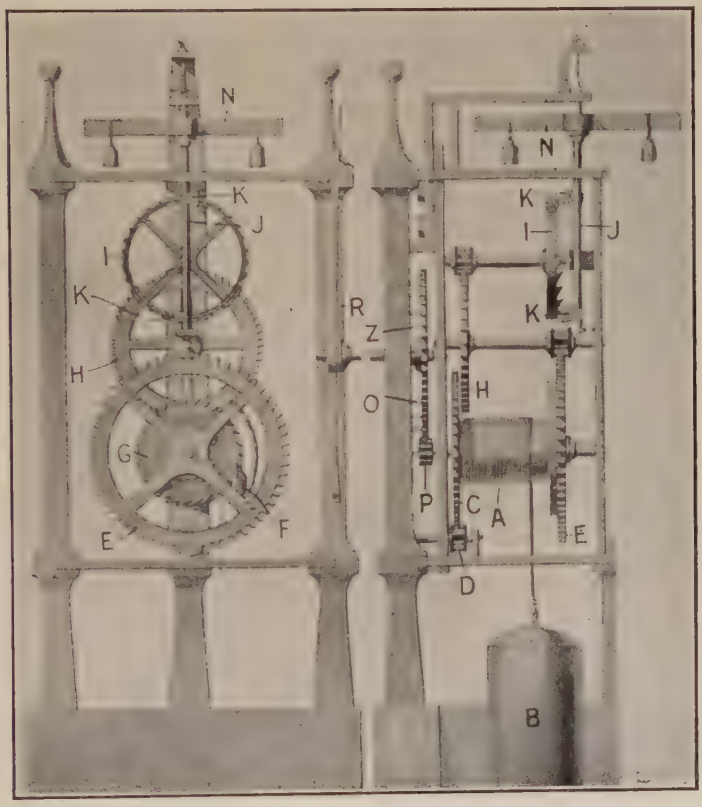


Fig. 50.—Going train of de Vick's clock.

describe this device in detail, since it is in common use, amongst other things for winding up the cords of lawn-tennis nets. The effect of this connection is to allow the barrel to turn without actuating the great wheel while the clock is being wound, but to compel the wheel to turn with the barrel when the weight is in action. The great wheel drives a pinion on the arbor of which is the second wheel *H*, and this in turn drives a pinion on the arbor of which is the third or 'scape wheel *I*. This last wheel is called a "crown

wheel," since its teeth project sideways. They are formed like those of a saw in order to enable the wheel to take its part in a device for controlling the speed called the *escapement*, which converts the machine from a mere train of wheels into a proper piece of clock work.

"The escapement is one of the most difficult parts of the clock to describe, and wants to be seen to be appreciated properly. However, on account of its essential character the attempt must be made. A vertical spindle *J* called a "verge"—probably from the Latin *virga*, a rod or twig—stands diametrally across the crown wheel. Its lower end rests on a bracket, while its upper end is suspended by a cord which helps to take the weight off the bracket. It is provided with two small leaves or plates *K*, *K*, called *pallets*, opposite the teeth at the top and bottom of the crown wheel. The pallets are set at right angles to one another, or a little more, and engage alternately with the teeth of the wheel. When, for example, the steep side of a tooth at the bottom of the wheel encounters the corresponding pallet it pushes the pallet to one side, thereby turning the verge on its axis and causing the upper pallet to enter the gap between two teeth at the top of the wheel. When the lower pallet has been entirely pushed aside so that the acting tooth can pass it, the wheel, and therefore the whole clock mechanism, advances with a little jump, which, however, is soon checked by the contact of the upper pallet with the steep side of one of the adjacent teeth. The pressure of this tooth now reverses the rotation of the verge, and the whole process is repeated, the motion of the verge being continually reversed and a tooth of the crown wheel released each time. To prevent this motion from proceeding too fast the verge carries a cross-bar or balance *N*, with adjustable weights for regulating the rate of oscillation; the farther the weights from the verge axis the slower the oscillations.

"A feature of this escapement mechanism is the recoil which it produces in the clock train. When a pallet encounters a tooth of the crown wheel, the motion of the verge is not stopped instantly, owing to the momentum of the cross-bar and weights. Some little time elapses before the motion is stopped and reversed, during which time the crown wheel is forced around slightly in the opposite direction to that in which the driving weight *B* urges it. The motion of the whole train is thus to a slight extent reversed, and the driving weight raised at every escape of a tooth. This effect is technically called recoil. It is an imperfection of the mecha-

nism, for though the power expended in lifting the clock weight is partly recovered by the subsequent fall of the weight, it is not wholly or even largely so, on account of the friction in the train and the loss in reversing the wheels and the balance."[158]

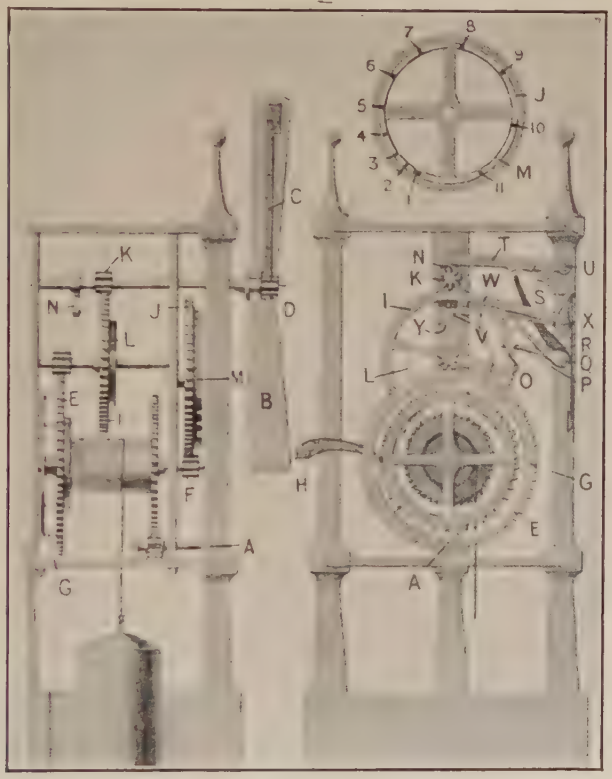


FIG. 51.—Striking train of de Vick's clock.

The striking mechanism of de Vick's clock is shown in Fig. 51.[159] The general features of the apparatus are concisely explained by Bolton:

"The general layout of the striking train does not call for special description, as it is similar to the going train and is actuated in the same way by a weight which is wound up by a key applied at *A*. The governing mechanism is, however, different. In the present instance the restraint is effected by means of a fan *B*,

[158] BOLTON, pp. 55–58.

[159] BOLTON, Plate VI, facing p. 85.

which is loose upon its arbor but is caused to rotate by spring pawls *C* engaging with the teeth of a ratchet wheel *D*. Thus the wheel train, while running down, drives the fan which checks the motion by air resistance. When the wheel train stops, the fan runs on for a few turns, but is quickly brought to rest by air resistance and by the friction of the pawls upon the ratchet wheel.

"Upon the arbor of the great wheel *E* is fixed a pinion *F* of eight teeth, and on the face of the great wheel are eight pins *G* which engage successively with the tail of a lever *H* and thus cause the clock to strike. The other end of this lever actuates the hammer which strikes the bell. The great wheel meshes with a pinion on the arbor of the second wheel *I*, and the pinion *F* with another wheel *J* of 78 teeth. The gearing is such that the second wheel *I* rotates once for each tooth of the wheel *J*, or, which is the same thing, the wheel *J* rotates once for every 78 rotations of the second wheel. The wheel *J* rotates once in 12 hours, and as during this time the hammer in striking the hours from 1 to 12, inclusive, must hit the bell seventy-eight times, each tooth of the wheel *J* and each complete rotation of the second wheel *I* correspond to one stroke. The second wheel drives the fly arbor by a pinion *K*, and it also carries on its face a circular hoop *L*, part of which is cut away so as to leave a considerable gap as shown clearly in Fig. 51 (rear elevation). Upon the face of the wheel *J* is the counting disk *M*, as shown separately at the top of Fig. 51. The counting disk has on its edge 11 notches numbered 1 to 11. Ten of these are of the same size, the remaining notch, numbered I, being twice as large. The notches are unevenly spaced, so as to leave full parts between them of progressively increasing length starting from the notch *I*. Upon the fly arbor is an arm *N* provided with a pin. The objects of these features will be explained subsequently.

"All this mechanism is, of course, at rest in the intervals between striking, and is entirely separate from the going part of the clock. We now pass on to its connection with the going part, by which it is started at every hour and stopped when the proper number of strokes have been delivered. The large wheel *Z* of the hand train, Fig. 50, which, it will be remembered, rotates once in 12 hours, has twelve equally spaced pins *O* projecting from its face, each pin corresponding to an hour. One of these pins is shown in Fig. 51 (rear elevation). It appears on the face of the wheel *I*, but this is an accident in the drawing. It does not belong to this wheel, but, as before stated, to the wheel *Z*, part of which is shown

by dots behind the wheel *I*. These pins engage in succession an arm *P*, called by French writers the *pied de biche* or hind's foot. The hind's foot is carried on a long arbor *Z*, which extends from the front of the going part to the rear of the striking part, where it carries two other arms *R* and *S*. An end only of the arbor *Q* is shown in Fig. 51. The object of the arm *S* is to lift a detent or lever *T* pivoted at *U*, though from the drawing, which is somewhat imperfect in this respect, it might appear scarcely capable of so doing. This, however, is the intention. The function of the detent *T*, which is called the "preparation detent," is to catch the pin on the arm *N* at the proper moment, as will be explained presently. The function of the arm *R* is to lift two detents *V* and *W* which are both fixed on the same arbor *X* and move together. The detent *V* is called the "cock detent" from the shape of its head, which, as Moinet says, "bears a faint likeness to the head of that animal." The likeness is certainly not striking in the drawing, but the writer has seen cases in which it is much closer. The acting faces of the cock head are two; one of these projects at right angles to the arm *V* and is shown in engagement with one end of the hoop *L*, while the other, shown at *Y*, which joins on to the former, has a much lesser slope of 30 or 40 degrees only. The other arm *W* is the counting detent. It terminates in a claw which, in the position of the mechanism shown in the figures, rests in one of the notches 1–11 in the counting disk *M*. None of these detents appear in Fig. 51 (side elevation), but of course the reader will realize that this omission is merely to avoid confusion in the drawing.

"The action is as follows: The parts being in the position shown, the mechanism is restrained from movement by the engagement of the right-angled acting face of the cock head with the end of the hoop *L*, while the claw on the counting detent *W* rests in one of the notches in the counting disk *M*, whichever happens to be uppermost. One of the pins *O* on the hour-hand wheel is shown about to engage with the hind's foot *P*. As the hour-hand wheel revolves, the pin *O* lifts the hind's foot, raising at the same time the arms *R* and *S*, and, therefore, the preparation detent *T* and the detents *V* and *W*. When thus raised, the detent *T*, the end of which is bent at right angles from the plane of the rear elevation, Fig. 51, comes into the path of the pin on the arm *N*, so as to catch it in its highest position when the arm revolves. Meanwhile, the cock head also rises slowly, and as soon as the end of the hoop *L* is

freed from the right-angled acting face, the mechanism begins to move. The end of the hoop then slides on to the acting face *Y* of the cock head, and the arm *N* gives a half turn, but its pin is almost immediately caught by the end of the preparation detent *T*, thus preventing further movement of the mechanism. This action, called the preparation or warning, gives rise to the noise heard in clocks shortly before they strike. The claw on the counting detent *W* is not necessarily lifted at this stage completely out of its notch, but its seat in the notch is sufficiently loose to allow of the slight movement of the mechanism which constitutes the preparation, although the counting disk rotates slightly in the process.

"This state of affairs continues for some few minutes, the pin *O*, and therefore all the detents, rising slightly but nothing else happening until the pin *O* passes the point of the hind's foot *P*, which then suddenly drops. This is timed to happen exactly at the hour. The result is that the preparation detent *T* also drops, releasing the arm *N*, and therefore the whole train. The detents *V* and *W*, however, do not drop, since the sloping face *Y* of the former rides up on to the hoop *L*; in so doing it also raises the claw of the detent *W* out of the notch in the counting disk if it is not completely out of the notch already. Thereupon the mechanism proceeds to move, the wheel *I* rotating until the gap in the hoop *L* is again presented to the cock head, which would then drop into the gap were it not that the counting disk has meanwhile rotated enough for the notch to move away from the claw on the counting detent *W*, which therefore now rides upon the solid part of the counting disk separating each gap from the next. The cock head is thus prevented from engaging with the end of the hoop *L*, which proceeds to perform a second rotation, and so on until the next notch is presented to the claw on the counting detent. The cock head can now drop into the gap in the hoop and so stop the mechanism, and when it drops the counting detent claw also drops into the notch. At each rotation of the hoop a blow is struck on the bell by one of the pins on the great wheel *E*. The intervals between the notches 1, 2, etc., on the counting disk increase progressively, as before stated, each permitting one more rotation of the hoop, and therefore one more hammer blow, than the last. An exception should be noticed in connection with the notch numbered *I*. When the counting detent claw first drops into this the clock has just struck twelve, and since one o'clock corresponds to one rotation only of the

hoop *L*, it is sufficient merely to widen notch number *I* to twice the width of the others in order to stop the mechanism after a single rotation of the hoop. This accounts for there being 11 notches only instead of 12 as might have been expected."[160]

The general significance of de Vick's achievement is attested by the conspicuous position given the description of his clock by the notable French clock maker, Moinet. He describes it in minute detail as an example of the simplest embodiment of the essential principles of clock making. His judgment of the actual mechanism is none the less indicative of the precise nature of the achievement. It was a "naive" piece of mechanism, still "crude," so that in comparison with modern instruments it would "scarcely seem to be a clock." The essential principles were perceived, but much remained still to be learned. Improvements were necessary in every respect, especially as regards the design and adjustment of the gearing and as regards the improvement of the balance and the escapement. Even in the later nineteenth century Moinet complained that the importance of refinements in the adjustments of the gears was neglected because clock and watch makers failed to realize that these matters were no less important than improvements in the general forms of the controlling mechanisms.[161]

The early clocks were made at the anvil of a general smithy with a technique developed by blacksmiths at work on mill gears. Inevitably, such instruments embodied a strange combination of brilliance in conception with a deficient technique of construction, but for this very reason they stand at the beginning of a long process of refinement in mechanical concepts which bridges the gap between the blacksmith and the modern tool maker. Some of the phrases of Reuleaux are especially significant in this connection. Mechanical progress, he says, moves from mechanisms dominated by "force-closure" to mechanisms dominated by "pair or chain closure." The wind and water mills of the fourteenth century, the water hammers of the fifteenth century, the steam engines prior to Watt, and in some measure long after, were all dominated by force-closure. Gravity, internal stresses, or the muscular force of the operative played an important rôle positively or negatively in the functioning of the machine and in the maintenance of the proper relations of the parts to each other. Motion was imperfectly constrained. In the clock, force-closure must

[160] Bolton, pp. 84–89.

[161] Moinet, "*Traité de l'horlogerie*," Vol. I, pp. 54, 73, 105–106.

needs be reduced to a minimum, its substantial presence impaired the efficiency of the mechanism. In the general design of the mechanism, therefore, little force-closure remained, but for a long time much casual force-closure remained in the imperfections of the wheel work. Reuleaux says:

"Toothed wheels furnish us with another example. Although they have been known for thousands of years, their improvement today is still essentially in the direction of excluding force-closure, that especially which has remained with the "clearance" or "freedom" allowed between the surfaces of the teeth, and which has often enough made itself disagreeably felt . . . During the Middle Ages, and in the last few centuries, the freedom has been more and more reduced, as greater care has been taken to find the kinematic condition to be fulfilled by the form of the teeth profiles, until we have now succeeded in reducing it to a very small fraction of the pitch. During the last century, the wheel and its teeth gradually came to be understood as forming one whole, and the teeth profiles were then looked at in a new light. I believe that in a few decades it will be the rule to employ spur wheels working without any clearance between the teeth."[162]

VI

The placing of de Vick's clock in the tower of the royal palace was significant, not only as marking a stage in the development of the clock, but also as the basis of the final establishment of modern methods of reckoning time. From an early date in antiquity, two general modes of reckoning had been in use. The general community divided day and night into hours or periods, identical in number throughout the year, but variable in duration because of the variations in the length of daylight. Ultimately both day and night were divided into 12 hours. Sun dials could be constructed to record these variable hours, and by appropriate dials the water clocks could be adapted to record variable hours, though the mechanism itself was commonly arranged to measure equal intervals of time. Astronomers and some other scientists, however, began at an early date to reckon time in equal hours, taking the hours of the equinox as standard. The use of equal hours competed in some measure with the use of the variable hour, especially in the early Christian period, but during the early Middle Ages the variable hour dominated general practice, chiefly because the

[162] Reuleaux, pp. 237–238; and more generally, pp. 226–242.

liturgical practices of the church were based upon the variable hour or combinations of variable hours into groups for liturgical purposes. There were divergencies in practice, and on the whole the liturgical periods tended somewhat to displace even the reckoning of hours. In civil life, on the other hand, the reckoning in terms of equal hours became more common, but the practice made no great headway until the close of the fourteenth century. The change coincides with the development of the mechanical clock, but it seems wrong to represent the new clock as a primary cause of the change.

Charles V of France took the first decisive step towards breaking down the dominance of the liturgical practices of the church. After the installation of his new clock, he ordered the hours and quarters to be struck in all the churches of Paris, according to the time given by the Palace clock, and at Vincennes according to the clock at the château. As these clocks counted equal hours, the new order did much to extend the vogue of the equal hour. This practice spread through northern Europe. For a considerable period, the day began at sunrise, but in the following century, the hours were counted in series of 12 from noon and midnight. Italy followed a different practice, counting the hours continuously from 1 to 24, beginning an hour after sunrise.[163]

No clearly marked changes in the general features of the clock occurred between the perfection of the foliot balance with the verge escapement and the application of the pendulum in the second half of the seventeenth century. The period was marked by the extension of the use of clocks and by improvements in the detail of construction. Three fairly distinct forms of clock may be distinguished: tower clocks, which indicated and struck the hours; cathedral clocks, which indicated the time and also displayed astronomical movements and mechanical puppet shows; and domestic clocks, for private apartments. The general mechanical features of all these types were identical, save for the complexities developed by the more elaborate cathedral clocks. These clocks were generally located inside the cathedrals, and consequently exhibit various external features that would have been impractical in positions exposed to the weather. By 1500, few towns were without some tower clock, but domestic clocks, though widely diffused among the wealthy, were not common in Europe, as a

[163] Bilfinger, G., "*Die mittelalterlichen Horen und die modernen Stunden*," Stuttgart, 1892; Wins, pp. 96 *ff*.

whole, until a later period. Later writers imply that clock making was so highly developed in Nuremberg in the fifteenth century that domestic clocks came into more general use in central and southern Germany than elsewhere in Europe. These German clocks of the fifteenth century were among the first made to indicate minutes and seconds, and some use was made of them by astronomers. Waltherus, Landgreve of Hesse, a pupil of Regiomontanus, made use of a clock in astronomical observations as early as 1484: commonly regarded as the earliest application of the mechanical clock to scientific use. We are told that the clock measured accurately the interval between the transits of the sun from noon to noon.

In the last quarter of the sixteenth century, clocks were used by Tycho Brahe at the notable astronomical laboratory, Uranienberg, on the island of Huen. There was one large clock and three smaller ones, indicating minutes and seconds as well as hours. The descriptions of the great mural quadrant, used for observing transits, imply that the time was taken by readings from two clocks; the mean reading being taken as correct.[164] In an earlier work, however, the clocks are mentioned and their insufficiencies are discussed. It seems to be admitted that the clock was relatively adequate for measuring long periods of time, and that no significant errors would appear in taking from them the time between transits of the meridian, but for other kinds of work requiring more accuracy they were not regarded as trustworthy. Errors due to changes in atmospheric pressure and temperature are mentioned. In winter, the clocks were kept in a heated room at a relatively constant temperature. There were also defects in the wheel work which led to irregularities of operation. Tycho Brahe concluded that clock time was not sufficiently accurate for work on the stars where an error of 4 seconds, "which a clock may easily lose in a few hours," would make a difference of 1 minute in the position of the star. For these purposes, time was measured either by direct astronomical observation of the positions of particular stars or by weighing the mercury delivered by a device based on the principle of the water clock.[165] Moestlin, a contemporary of

[164] Tychonis Brahe, "*Astronomiæ instauratæ mechanica*," 1598. "*Opera omnia*," Vol. V. p. 29; with plate showing two clocks.

[165] Tychonis Brahe, "*Astronomiæ instauratæ progymnasmatum*," 1572. "*Opera omnia*, Vol. II, pp. 156–158. "*Epistolarum Astronomicarum*, Vol. VI, p. 69. Both passages are summarized by Bailly, *Histoire de l'astronomie moderne*," Paris, Vol. I, pp. 398–400, 714, 1785. The statement about the rate of loss of the clock is omitted by Bailly.

Tycho Brahe, made use of mechanical clocks in his astronomical observations.[166]

On the whole, these references confirm the judgment of Bolton from his study of the extant works of the Dover Castle clock. Prior to the application of the pendulum, the clock was inaccurate for the shorter intervals of time, measurably accurate for the longer intervals. Presumably, some substantial improvements were made in the accuracy of clocks during the fifteenth and sixteenth centuries, despite the persistence of the essential elements of the controlling mechanism. By the close of the sixteenth century, the clock was almost good enough to be considered an instrument of precision: for some types of scientific work it might suffice, though elements of possible error remained a serious factor in the closest work.

[166] Berthoud, Vol. I, pp. 58–59.

Chapter VII

LEONARDO DA VINCI; ENGINEER AND INVENTOR

I

Despite the rapid spread of knowledge of the work of Leonardo da Vinci in the various technological fields the opinion still prevails that art was his predominant interest: more important both in his own eyes and for the development of European culture. Grothe, one of the most discriminating students of the technical work, felt constrained to admit that Leonardo's accomplishments in these fields fell short of the highest distinction. Miss Taylor, interested more especially in the inner life of Leonardo, reached a similar conclusion. "The essential Leonardo," she says, "is the artist." His scientific and technical work served to balance an intense emotional life that was given a peculiar quality by the persistent ascetic tendencies. The rationalistic features of the technological work gave him a poise that saved him from mental breakdown or aberration; but Miss Taylor feels that the value of these interests was personal rather than general. The accomplishment in science was merely incidental to his achievement of a balanced intellectual and emotional life.

Miss Taylor thus recognizes clearly the persistent and fundamental importance of the scientific interests, which is one of the most striking objective facts about the career of the great Florentine. No period of his life is given over wholly to any single type of activity and his greatest achievements in the fields of art and science were simultaneous. The work, on both the Last Supper and the model of the equestrian statute of Francisco Sforza, was substantially contemporary with the early notes on science, the earlier drawings of machinery, and important work on canals and the principles of hydraulics. The period marked in art by the pictures of St. Anne and the Virgin, the Mona Lisa, and the cartoon for the Battle of Anghiari leaves notable records of the scientific work. Important work was done on pure science in physics and geometry; the dissections for the anatomical studies were begun; the fortresses of the Romagna were inspected and

alterations and improvements were presumably suggested; the canal projects of the period involved maps, plans, and further work on hydraulics.

When Leonardo returned to Milan in 1506, under the patronage of the French, his skill in painting was the primary factor in the mind of the new patron, Charles of Amboise. But the versatility of Leonardo was quickly impressed on this new Macænas. The notebooks afford striking evidence of the vigorous prosecution of technical and scientific work. The "treatise" on painting was begun and much of the material completed. Studies of the flight of birds were apparently concluded. The completed treatise on hydraulics (Leicester Ms.) probably belongs to this period. The anatomical studies were practically completed, though there are some drawings of a later date. At Rome, 1513–1516, scientific work seems to have commanded most of Leonardo's attention; though more from necessity than choice. There was much jealousy between the Florentine and the Roman artists and Leonardo found it difficult to secure much patronage for artistic work. The service of Francis I offered a more hospitable environment, but paralysis deprived Leonardo of the use of his right hand shortly after he reached France and painting became impossible, though he drew and wrote with his left hand. The artistic work of this period in France was restricted to architectural plans. It is possible that the designs of the spiral staircase at Blois were his, and he may have furnished the primary designs for the château at Chambord, but there is no adequate documentary proof of the extent or nature of Leonardo's influence upon the building programs of the king. Scientific and technical work continued until a short time prior to his final illness.

The scientific and technological studies were thus a constant feature of Leonardo's activity, and it is somewhat artificial to attempt to consider this aspect of his work separately, for the two activities were not mere compartments of his mind, reduced to a kind of external contact. Nearly all his scientific and technical work involved the use of his artistic powers, and whether his notes were mere pen and ink sketches or carefully finished perspective drawings, they reveal a new quality that was based upon the essential artistry of the man. Nor is the painting divorced from this scientific curiosity. Much of the special quality of the work of Leonardo and his pupils comes from the attempt to visualize the inner life of the subjects. The art of Leonardo is based upon

this essentially spiritual conception of life. The body is regarded not as something complete in itself, but as an expression of an inner life, and it is not unduly imaginative to associate this view of life with the scientific work. Leonardo was fascinated by these notions of inner forces: the spiritual forces of human character; the physical forces of nature. All external phenomena were to him manifestations of these universal forces; all phenomena, all animal and human forms were interesting because they were expressions of force. Art and science were thus intimately related in Leonardo, and in the judgment of his personality these elements can hardly be separated. Freud believes that the scientific interests inhibited artistic work and finally became the dominant activity.

Our judgment of the relative quality of accomplishment in these different fields of activity is inevitably influenced by the character of the records and by the essential differences in the character of such diverse accomplishments. Scientific and technical results are not in themselves explicitly individualized. Even the most talented individual does no more than modify the existing body of knowledge in ways that lead to further change and development. The only individuals who are clearly emphasized in the history of science are those who accomplish notable syntheses of the work of many predecessors. Such personalities are made a part of the historical record by actual force of circumstances; the work of the others is largely obscured and lost unless the records of individual work are singularly complete. The history of science thus has at all times a small number of great names, but this list is by no means a complete list of talents of the first magnitude. The process of invention tends to obscure the individual even more completely. Invention does not naturally leave a general written record: the work of each individual is built into complex mechanisms which can be analyzed and dated only with the greatest difficulty. The development of proprietary interests in patents has tended to result in a more substantial record of individual work, but these developments are relatively late and the materials created still leave many elements of doubt, and the actual history of many recent inventions is in fact ill known.

The commonly known names of inventors of the last century and a half reveal all the caprices of public hero worship. Many names of notable inventors have been largely forgotten, or their genuine achievements remain unrecognized, while some casual

item persists. Other names are given a merited place in public esteem though the nature of the accomplishment may perhaps be wholly misunderstood. The extent of these errors may be readily ascertained by a comparison of the statements in general text-books and histories with the primary biographical and technical material on such personalities as Arkwright, Samuel Crompton, George Stephenson, Oliver Evans, Fulton, and Eli Whitney. The achievement of the artist, on the other hand, is an end in itself: explicitly individualized, commonly a matter of positive record, and at the best of permanent professional value despite changes in contemporary taste and style. The achievement of the inventor and technologist, on the contrary, is merely a contribution to a flowing stream of accomplishment in which the identity of the individual's work is obliterated by all the natural circumstances of social life. Scarce any piece of apparatus survives its inventor without transformation, and even the most brilliant concepts seem simple once they become commonly known. The quality of achievement in the technical field can be judged only in terms of the contribution of the individual to the development of science and technology, and all the facts of the record must be considered in such a judgment. There is a stage in which progress is explicitly marked by an achievement such as Newton's "Principia," or Watt's condensing engine; but there are other stages in the process of accomplishment that are not so clearly marked, though the magnitude of the achievement is no less great. The initial steps in a great revision of thought involve serious resistances and these early accomplishments reveal powers of innovation of the first magnitude. Those who stand at the beginning of new things secure less public acclaim than those who bring to final statement a body of new truth or who bring into practical use various new technical devices. It is thus with Leonardo. He laid the foundations of the new experimental sciences; he broke away from mere empiricism to concepts of an applied science of mechanics capable of general application throughout the whole industrial field. The record of his work was left in manuscript form, at a time when the new art of printing was beginning to create new opportunities for publicity. Materials for various treatises were being prepared but final composition was postponed in most cases, and only two or three of the series were actually put together under his hand. Of the machinery sketched in the notes, the most novel features were too far in advance of the technique of the period to admit of

practical application. But much of the inventive effort was worked into current practice by Leonardo himself and those around him, so that even apart from his manuscripts these devices exerted a powerful influence upon his time. Recent studies by Duhem in the field of science, and by Theodor Beck in the field of engineering show that the influences of Leonardo are clearly perceptible for a full century. Directly or indirectly, though without explicit recognition, his influence appears in the scientific and technical treatises of the notable Italian school of the sixteenth century, and even in some French and German treatises.

The notebooks of Leonardo mark the beginnings of the scientific work that began to achieve conspicuous results only at the hands of Galileo and Kepler. They also mark the beginning of the modern treatises on hydraulics and applied mechanics that are represented by the work of Agostino Ramelli (1588), Jacques Besson (1568), Vittorio Zonca (1607) and Castelli (1628). The last three treatises were published posthumously, and in some instances at quite an interval. They are by no means the only treatises on mechanics in which the influence of Leonardo is apparent, but they constitute the chief literary evidence of the extent and character of his contacts with his successors, and it is noteworthy that Besson and Ramelli carried these influences into France just as Strada carried them into Germany.

Accustomed as we are to the predominance of a written record in the applied sciences, we are prone to think of Leonardo's work as incomplete because the treatises projected were not completed and printed. We are likely to misjudge the significance of Leonardo's notes and projects and the influence of his work upon his time. Treatises on applied science were then the exception rather than the rule; very few had appeared in Europe or the East since the decline of the second Alexandrine school. Some Arabic treatises on water clocks have been referred to previously, and Alfonso X of Castile had a series of treatises prepared upon astronomy and related subjects. The treatise of Theophilus on the arts was only incidentally concerned with mechanical apparatus. Robert Valturius prepared a treatise on the art of war which was brought out in print during Leonardo's lifetime. But despite the historical value of these treatises, the manuscript sketches of the German engineers of the fifteenth century afford clear evidence that the mechanical knowledge of the time was very imperfectly and incompletely reduced to graphic form. The

tradition was largely transmitted by direct instruction: even the Greek treatises had been supplementary only to direct instruction both at the time of their composition and in subsequent periods. New standards of education, new means of publication, new regard for the scientific principles implicit in the engineering field combined to alter the relative importance of oral and written presentation of these subjects. The new ideas were not confined to Leonardo, but his lifetime marks a definite transition and his efforts contributed significantly to the change. With him graphic record became a consuming passion. Important notes and trivial jottings went down on paper: not infrequently upon the same sheet. The earliest dated material we now have is from the year 1488, and thereafter notebooks were kept. Some little attempt seems to have been made to classify material by subjects, so that several notebooks would have been at hand simultaneously, but no rigorous attempt was made at arrangement. They were a complete record of his mental activity and were intended to be the basis of a series of treatises. The project included treatises on painting, on the nature, weight, and motion of water, on the flight of birds, on motion, on impacts, on weight, on moments of energy, on the elements of machinery. The only treatises put together by Leonardo himself are the treatises on the flight of birds, and the treatise on the nature and motion of water represented by the Leicester manuscript which has only recently been published. The treatise on painting and the treatise on the nature, weight, and motion of water that have long been available in print were compiled from the notebooks by students of Leonardo or later copyists in the employ of Cardinal Barberini. With a similar amount of editing, material representing practically the entire scheme could be compiled even from the notebooks now extant. The resultant treatises would be about as thoroughly composed as many of the treatises on similar subjects in the sixteenth century. In addition to the treatises projected, there are materials for substantial treatises on human anatomy and upon the anatomy of the horse. Furthermore, the projects mentioned in the notes indicate only one treatise on machinery, though the material available is very extensive, and is comparable in range to several of the sixteenth-century publications. There is a complete series of mills with arrangements for the use of all the sources of power: wind, water, horses, tread mills, cranks turned by men. There are drawings covering all the forms of pumps and hydraulic apparatus, con-

taining many novel features for the application of power. Individual elements of machinery are abundant and some attention was clearly given to the parts, as such. There is a fairly comprehensive series of drawings for the machinery of the textile industry and the manufacture of metals. The drawings of artillery, methods of its manufacture, and the art of fortification are more significant and more extensive than in Valturius, and Leonardo's material is not notably surpassed in the treatise by Lorini published in 1597, either in the parts strictly concerned with military apparatus or in the parts concerned with general mechanical devices.

II

The notebooks are at once a record of existing apparatus and of Leonardo's attempts to apply the principles known to him to new problems. New and old are hopelessly interwoven so that it is not always possible to distinguish them. Some writers have held that Leonardo gave systematic instruction in mechanical subjects and in painting at Milan, on the strength of a number of scrolls bearing the legend "*Leonardi Vici academia.*" The projected treatises are presumed to have developed out of this instruction. That instruction was given more or less formally in painting can scarce be doubted; but there are no adequate grounds for assuming that similar attention was given to the sciences and to mechanical subjects. The mechanical work bears such close relation to the activities of Leonardo in engineering work that no other motives are necessary. The studies of machinery were, in part, the outcome of works undertaken for his patrons in architecture, canal building, or in military engineering. In part, they were the result of deliberate attempts to invent new industrial appliances which were to be a source of gain or, in the case of the flying machine, a source of fame.

The known activities of Leonardo in canal building begin with the work of improving the Martesana canal and the navigation of the Addio in the vicinity of Milan (*c.* 1490–1499). In 1503, when Leonardo was in Florence, a canal was planned to divert the Arno from its course in such a way as to prevent the provisioning of Pisa from the sea. This military project, however, was not effectively carried out. But Leonardo conceived a project of connecting Florence with the sea by a canal *via* Serravalle. The canal was designed to furnish power to mills, to supply water for irrigation,

and to supply better facilities for transport. The problem of the hills at Serravalle could not be met within any reasonable costs and no attempt was made to carry out the scheme, though a notable series of maps and sketches was prepared. In France in 1516–1517, plans were prepared for canalization of the Cher at Romorantin. The work actually executed was therefore not extensive, but such problems occupied Leonardo's mind for many years, and they leave a record that includes the treatise on hydraulics, and drawings of all types of apparatus for excavation, pumping, dredging, lock construction, and bridging of canals with drawbridges. Much of this apparatus must be thought of as representing current practice, and the innovations were mostly of the type that would be adopted. Many of them appear in later treatises; either because they had already been adopted in practice, or because they became known through the notebooks and were actually introduced into practice after Leonardo's death.

The patronage of Sforza and of Francis I involved various architectural commissions and to this work we owe many sketches: cranes, hoists, compound pulley blocks, as well as the architectural drawings themselves. The military apparatus is also closely associated with Leonardo's direct obligations, first in the service of Sforza, later in consultation with the officers in charge of the siege of Pisa, and in the short interval of service under Cæsar Borgia. There are many innovations in the designs and types of cannon and in fortress construction. During Leonardo's stay in Rome, 1513–1516, he was engaged apparently in some work at the mint and the schemes for mechanizing the process of coinage are the outgrowth of these contacts. His work seems to have left some permanent impressions on the practice of the papal mint which were fully developed shortly after by Benvenuto Cellini. At Rome, too, Leonardo was at work on a process for the construction of large concave mirrors to be used as burning glasses. For this project, he used a shop at the Belvedere and was assisted by a German workman who exasperated him beyond measure by his lack of discipline. In the end, after vain attempts at black- mail, the workman stole all the secrets of the process and went into the business of supplying mirrors in quantity for the local fairs.

Beyond these contacts with practical affairs, all of which were of direct practical importance, there were three projects which had no known immediate practical value. The notebooks contain

sketches for a relatively complete set of machinery for the woolen industry: a spinning machine; a power loom; a gig mill, for raising the nap of the cloth; and a shearing machine. In conjunction with the familiar fulling mill, these machines would have performed mechanically all the primary processes except carding. The spinning machine and the gig mill were sound in principle and embody features that subsequently were utilized, though there are no records to indicate the extent of indebtedness of later workers to Leonardo. The sketches for the loom and "flying" shuttle are incomplete, and though there are numerous schemes for the shearing engine the essential principle was naïve and incapable of development. Winding apparatus for the silk industry is also sketched. Some device for this purpose had long been known, but no sketches are available prior to this date. The principles involved exerted significant influence upon the industry, either directly through Leonardo or through Zonca, whose machine for silk winding is closely related to Leonardo's. Leonardo's sketches are not as complete as Zonca's and we have no means of knowing the nature of Leonardo's contacts with the industry.

Two projects seem to have been purely personal: a scheme for polishing sewing needles by machinery and the flying machine. These projects reveal most conspicuously the characteristic hopes of the inventor: the needle machine was to bring wealth, the flying machine was "to fill the world with its great fame."

One of the sheets with sketches of the needle machine is accompanied by the text:

"Early tomorrow, Jan. 2, 1496, I shall make the leather belt and proceed to a trial . . . One hundred times in each hour 400 needles will be finished, making 40,000 in an hour and 480,000 in 12 hours. Suppose we say 4,000 thousands (implying 10 machines) which at 5 solidi per thousand gives 20,000 solidi: 1,000 lira per working day, and if one works 20 days in the month 60,000 ducats the year."[167]

The meaning of this last figure will be apparent, if we remember that at that time Leonardo's yearly stipend from Ludovico Sforza was 2,000 ducats, and the stipends received later from Louis XII and Francis I were about the same. While at Rome, Leonardo received 33 ducats a month from Guiliano de Medici, or a little less than 400 ducats a year. Guiliano himself had a yearly

[167] Beck, V. D. I., p. 649.

income of 60,000 ducats.[168] Under the circumstances, the needle-making scheme bears all the marks of a money-making enterprise, and as this work was being done towards the close of Ludovico's rule in Milan, a time in which Leonardo stood in high favor at the court with every opportunity for the development of his art, it is possible to draw inferences as to the place that these mechanical efforts held in Leonardo's personal life. Like many an inventor in the centuries that follow, he had dreams of wealth and independence.

Although we have considerable knowledge of the details of Leonardo's life, we are ill informed of the precise character of his contacts with the craftsmen in the mechanical arts; but it is surely evident that the sketches in the notebooks are not merely the work of a detached observer endowed with an unusually vivid imagination. They are a record of daily work and of the projects suggested by the immediate tasks of the day, with some essentially personal schemes added. Many of the newer concepts of method would necessarily have been communicated to the craftsman working under this extraordinary Florentine, whose work carried him to many important centers of influence in northern and central Italy at a time of vital economic and technical growth.

Leonardo, however, did not cease to exert a direct influence upon science and technology even after his death, for the notebooks, though in manuscript, enjoyed a restricted but notable circulation. The entire mass of material was bequeathed by will to Francisco Melzi, a pupil and a devoted friend and admirer. Until Melzi's death in 1570 the manuscripts remained largely intact in his villa at Vaprio. Out of regard for the memory of Leonardo, many facilities for use of the manuscripts were given to proper persons. Jerome Cardan certainly worked with them at this time, and Vasari saw them. Some passages in Vasari imply that a few manuscripts had already passed into other hands. At all events, the manuscripts were a significant influence in the mid-sixteenth century, and the scientific and mechanical materials were cheerfully appropriated on a grand scale by Cardan, who constitutes one of the most important single sources of what we may call the vicarious publication of the manuscripts.

In 1587, a new period of influence began. Orazio Melzi entertained projects for the printing of various manuscripts, and when

[168] VON SEIDLITZ, "Leonardo da Vinci," Vol. I, pp. 204, 440; Vol. II, pp. 118, 169.

these failed attempted to sell portions of them. A selection of the anatomical drawings and sketches of art subjects was made, and also a selection from the mechanical drawings. One Gavardi undertook to sell these to the Grand Duke Francesco, but he died before negotiations were concluded and the project was abandoned. Gavardi made no attempt to return the manuscripts, but finally the representations of a young lawyer of Pisa brought him to due realization of his obligations to restore the manuscripts to Melzi and they were actually entrusted to the lawyer, Mazzenta, to be returned. Melzi, however, gave them to the lawyer, without more ado. They were turned over by the lawyer to his brother Guido, an engineer, who had them in his possession for a short time. Shortly after this, one Pompeo Leoni conceived the project of selling these manuscripts to the King of Spain, and Melzi was urged to ask the Mazzenta to return them. Some of them were returned and these manuscripts then proceeded on new journeys. The artistic drawings passed into the hands of the King of England in 1610 by way of a Spanish grandee, Don Juan de Espina, and the holdings of the royal family were subsequently increased by substantial purchases in Italy at various dates. The mechanical drawings were brought back to Italy and remained in the hands of Leoni and his heirs until they were purchased in 1625 by Count Galeazzo Arconati who was systematically collecting Leonardo manuscripts. Arconati secured the major part of the manuscripts and after refusing munificent offers from the King of England for the entire collection, bequeathed it intact to the Ambrosian library at Milan (December, 1636). Interest in the manuscripts was clearly strong at this time, for extensive copies were made for the Cardinal Francesco Barberini, a nephew of Urban VIII; and through these channels the Vatican library came into possession of important materials. The treatise on painting was finally printed (1651) from the Vatican text, and much later the compilation on the motion and measure of water (1802). The treatise on hydraulics by Benedetto Castelli (1628) is commonly supposed to have been profoundly influenced by the Vatican compilation from Leonardo's notes.

Some manuscripts of importance escaped Arconati's searches, and their history adds further testimony to the circulation of the manuscripts. The treatise on hydraulics now in the hands of the Earl of Leicester was purchased in Italy at the close of the seventeenth century. A manuscript concerned with physics and

mathematics, now at the British Museum was acquired by the Earl of Arundel in Nurnberg in 1636. Three small notebooks, now at the South Kensington Museum, were acquired in Vienna by the first Earl Lytton. After 1637, however, the primary scientific manuscripts were at Milan, where they remained until the invasion of Napoleon. They were then brought to Paris and many of them were never returned. The historical study began at that time. The essays of Venturi called attention to the significance of the work in pure and applied science, and since then the reconstruction of the history of science in the sixteenth century has proceeded steadily, bringing more and more detail to light upon the pervasiveness of the influences of Leonardo throughout the period.

III

The extent of the explicit contributions of Leonardo may be best appreciated by the following summary of his accomplishments in the fields of applied mechanics, hydraulics, and military engineering. The common attributions of these devices is also given; when the principles indicated by Leonardo required further development the name of the inventor perfecting the device is given in brackets:

	Formerly Attributed to:
Hydraulics:	
Principles of the flow of water	Benedetti Castelli, 1628
Theory of wave motion	Newton and l'Emy
Pressure in connected tubes	Pascal, 1653
Influence of pressure on fluidity	Stevinus; Galileo
Hydraulic Appliances:	
New details of pumps	Ramelli, 1588
Use of pendulum to drive pumps	Ramelli, 1588
	Besson, sixteenth century
Water screw with coil of pipes	G. de Rubeis
Centrifugal pump	
Improvements in canal locks and gates	
Dredge: two types	Besson
Hydraulic press (rather ambiguous sketch)	Bramah. 1796
Military Engineering:	
Polygonal fortress with outworks	A. Dürer. 1527
	Buonaiuto Lorini, 1597
Breech-loading cannon	
Rifled firearms	
Wheel-lock pistol	
Steam cannon (sketch)	

General Mechanics:	
a. Individual parts and pairs of mechanical elements:	
Antifriction roller bearing	
Band spring and fusee	Sixteenth century
Universal joint	[Philo of Byzantium] J Cardan, Robert Hooke; seventeenth century
Screw with square threads	
Conical screw	
Rope and belt drives, plain and crossed	Ramelli, 1588
Link chains	Vaucanson, Galle, eighteenth century
Bevel gears	
Spiral gears	
Stepped gears (incomplete sketch)	
Double-worm cam slot on a cylinder (developed beyond Hero's form)	
Various irregular shaped gears	
Various crank motions	
b. Machine tools and instruments of precision:	
Improvements on the lathe: continuous motion	Besson: Danner, sixteenth century
Improvements on drills and drilling apparatus	[Focq, 1770 Crillon, 1809]
Wood planer (plane to be moved by hand)	
Improvements on grinding and polishing wheels	
Appliances for cutting screws and nuts	
File cutter (sketch)	Mathurin Jousse, 1627: [Duverger, 1699]
Proportional compasses	J. Bürgi, 1603
Paraboloid compasses	Galileo
Various apparatus to measure wind and water pressure	Polhem, about 1700
c. Prime movers:	
Weight-driven clock work (applied to file cutter, turnspit, fan)	
Studies looking towards the turbine	Barker, 1745
Water wheel (incomplete)	[Fourneyron, 1823]
Turret windmill	Anonymous Dutch inventor of late sixteenth century
Tread wheel, worked from level of the center	Faustus Verantius, *c.* 1617
d. Textiles:	
Rope-making apparatus (sketch)	[R. March, 1784]
Silk doubling and winding	Zonca, late sixteenth century
Woolen spinning	Jürgens, 1530

Power loom (incomplete sketch)	
Gig mill	
Shearing engine (various incomplete studies)	
e. Metal trades:	
Rolls for forming iron staves for artillery making	
Rolls for forming gold bars for coining	
Hammer work for making gold bars	
Various metal punches	Benvenuto Cellini, 1528
Coinage forms	
f. Miscellaneous mechanical appliances:	
Studies of detail and assembly of the printing press: including an attempt at coordinating the motion of the press and the bed plate	
Improved pile driver: two sketches (based on early fifteenth century elements)	Delahire, 1707
Turnspit: two forms, one driven by clock work and falling weight regulated by a fly; another turned by the draft in the chimney	Zonca, sixteenth century
Fan driven by clock work and a falling weight	Strada, late sixteenth century
Wheelbarrow	Pascal / Agricola
Lamp chimney	
Ship's log	
Wagon with windlass drive	Haupt, 1649
Parachute	Lenormand, 1787

Leonardo thus left a record highly characteristic of an inventor: there are positive accomplishments, complete projects, and rough sketches of new mechanical concepts not carried by him to completion. The failure to impress his name more specifically upon the public was due to a caprice of history that is rapidly being corrected. Owing to the character of his work, the nature of his record, and the moderate interest in historical detail, the extent of his achievement faded gradually into obscurity in the latter part of the seventeenth century; to be recovered adequately only with the work of Grothe (1874), Richter (1883), and Theodor Beck (1900–1906). With Beck's studies of Leonardo and the other sixteenth-century writers, it has now become apparent that the study of modern mechanical engineering must begin with Leonardo. The mistaken attributions of the older literature are now being rapidly corrected, though the

process is far from complete, and there is now every ground for recognizing that Leonardo achieved the highest order of distinction as an engineer and technician.

The unique distinction of Leonardo as an engineer, however, is most strikingly displayed by the manner in which his work meets the qualifications set down by Reuleaux to mark the beginning of a science of machinery. He says:

"In earlier times men considered every machine as a separate whole, consisting of parts peculiar to it; they missed entirely or saw but seldom the separate groups of parts which we call mechanisms. A mill was a mill, a stamp a stamp and nothing else, and thus we find the older books describing each machine separately from beginning to end. So, for example, Ramelli (1588), in speaking of various pumps driven by water wheels, describes each afresh from the wheel, or even from the water driving it, to the delivery pipe of the pump. The concept "water wheel" certainly seems tolerably familiar to him, such wheels were continually to be met with, only the idea "pump," and, therefore also the word for it—seems to be absolutely wanting. Thought upon any subject has made considerable progress when general identity is seen through the special variety; this is the point of divergence between popular and scientific modes of thinking. Leupold (1724) seems to be the first writer who separates single mechanisms from machines, but he examines these for their own sakes, and only accidentally in reference to their manifold applications . . . So soon as the first Polytechnic School was founded, in Paris, in 1794, we see the separation between the study of mechanisms and the general study of machinery, for which the way had thus been prepared, systematically carried out."[169]

The notebooks afford abundant evidence of the existence of this separation in Leonardo's mind. There are many sketches of particular mechanical elements and pairs, and many studies of specific problems incidental to many machines, notably the various ways of converting rotary motion into a reciprocating motion, in various planes. Studies of machines are confined to the distinctive mechanism without any indication of the kind of prime mover to be used. Probably, Reuleaux underestimated some elements of early mechanical thought, because he thought of the tradition as based exclusively upon a written record. Leonardo's notes let us into the full content of his mind better than

[169] Reuleaux, p. 9.

formal treatises, such as those of Ramelli, Lorini, and Agricola. In the formal treatise, which was somewhat external, and only a supplement to the oral tradition, much of the general working methods of the engineer was deliberately omitted. It would hardly be safe to assume a profound difference between the methods and practice of Leonardo and those of his immediate successors, but even with some allowances Leonardo must be given a commanding place as the founder of a science of applied mechanics.

The range of Leonardo's mechanical work can be very inadequately appreciated without careful study of a large number of the drawings, but a few characteristic examples of his work will indicate more concretely than mere text description the quality of his mechanical studies. In Figs. 52 to 56, a number of devices are reproduced, most of them taken from isolated sketches in the notebooks.[170] Figures 52, 53, and 54 are studies in the conversion of

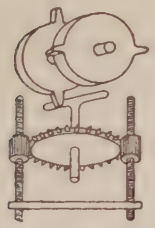


FIG. 52.—Wheel and pinions.

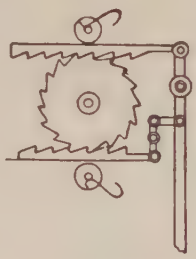


FIG. 53.—Swinging and rotary motion.

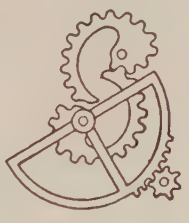


FIG. 54.—Study in gears.

rotary motion into various kinds of reciprocal motion. In Fig. 52 we have a study of a device for producing a reciprocating motion by the action of the wheels with cams upon the axle bar of the toothed wheel. The screws are alternately drawn in and pushed out. Figure 53 shows a method of converting a swinging motion into a rotary motion. The main lever works two saw-toothed rods against the face of a wheel with appropriate teeth. The rods are kept in contact by springs operating on antifriction rollers. This device also appears in the work of Lorini, 50 years later. Figure 54 is taken from the detailed sketches for the drawings of a cross-bow. The device is intended to give added power as the tension increases with the gradual drawing of the bow. It is an early

[170] BECK, G. M. B., pp. 321–323, Figs. 392, 401, 402; BECK, V. D. I., pp. 528, Fig. 24; 530, Fig. 38 (redrawn).

attempt to utilize irregular geometrical shapes in the production and transmission of motion. Figure 55 shows a pair of spiral gears. Leonardo remarks that they are more durable than a simple worm drive because the bearing surfaces are larger. Figure 56 presents one of a large number of applications of roller bearings, the axle of the wagon is presumed to be fixed in the hubs of the wheels. In drawings of pulley blocks, Leonardo approached more closely a correct concept of a complete roller bearing. He made use of the general notion in many connections and regarded the device as one of the "wonders of mechanical art," but he does not quite achieve a complete distinction between distributing the weight of the load and the diminution of friction between the moving parts. Thus, he writes in one place:

"With such an arrangement of roller axles it is indeed true that the weight is distributed among the various axles, but if these

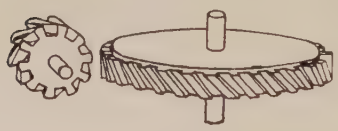


Fig. 55.—Spiral gears.

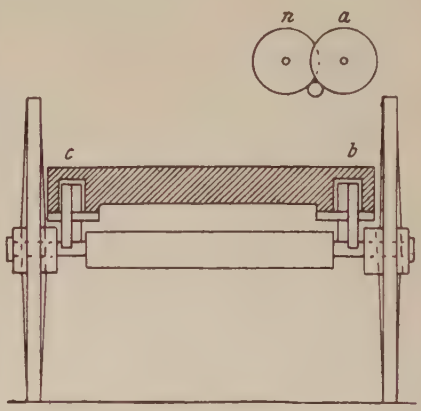


Fig. 56.—Antifriction rollers.

loads are added up the resistance will be found to be the same. Just as if we divide a pound into twelve ounces: when they are added up again they still make a pound."

Leonardo encountered in this problem of friction a serious theoretical difficulty which he did not solve clearly. Variants of the problem appear in other places in the notebooks. But despite partial failure, we find here a significant definition of a new problem which was destined to play a notable part in the development of physics and mechanics. He made most important progress towards the abstract concept of a frictionless medium and the separate analysis of the friction actually encountered in particular devices.

Figure 57[171] shows studies of link chains such as were later brought into general use by Vaucanson (eighteenth century)

[171] Feldhaus, "Leonardo," p. 81.

and Galle (1832). Although these elements are identical with the modern driving chains in every detail of construction, it would seem that Leonardo was proposing to use them for a somewhat different purpose, not wholly evident from the drawing.

The file-cutting machine shown in Fig. 58[172] is interesting from several points of view though there is no reason to suppose that such a machine was actually built. It is one of several instances of

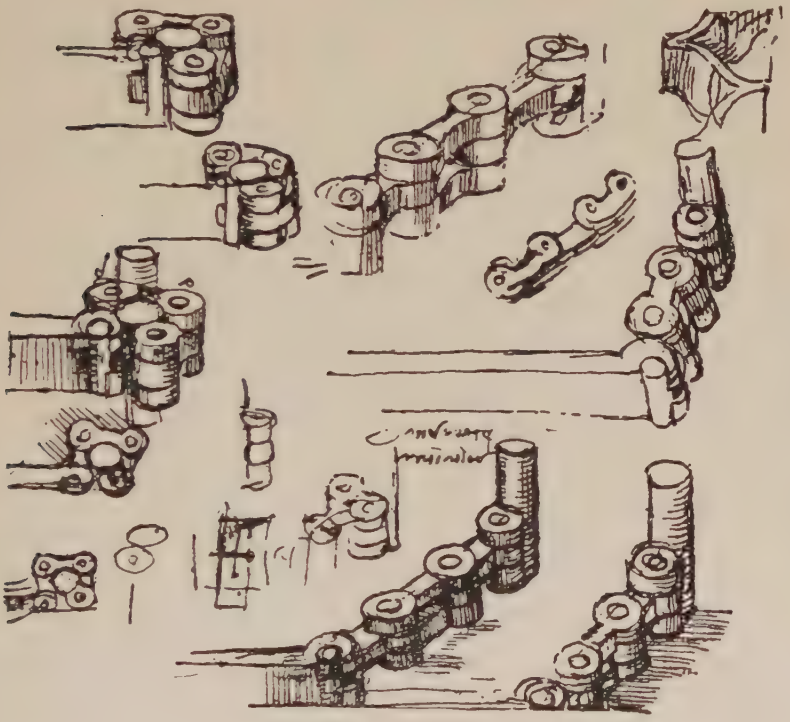


FIG. 57.—Link chains.

the application of clockwork to industrial mechanisms and thus marks a stage towards the notion of relatively automatic mechanisms which appears again and again in Leonardo's notebooks. There is thus direct evidence that the technique of clock making was exerting a measurable influence upon general mechanical concepts. The machine is to be driven by a falling weight, requiring attendance only for periodical winding from time to time. The file is cut by the blows of a trip hammer, and the movement of the block to which the blank is fastened is coordinated with the

[172] FELDHAUS, "Leonardo," p. 61.

movement of the hammer. The general principle employed here appears again in 1627 in the work of Mathurin Jousse and in the instruments that were finally perfected at the close of the eighteenth century, though some new features were then introduced. Leonardo's conception is said by Beck to be superior to the plan suggested by Duverger in 1699. There is no evidence that Leonardo built either a model or a test machine, and the apparatus seems to be rather light for the task proposed.

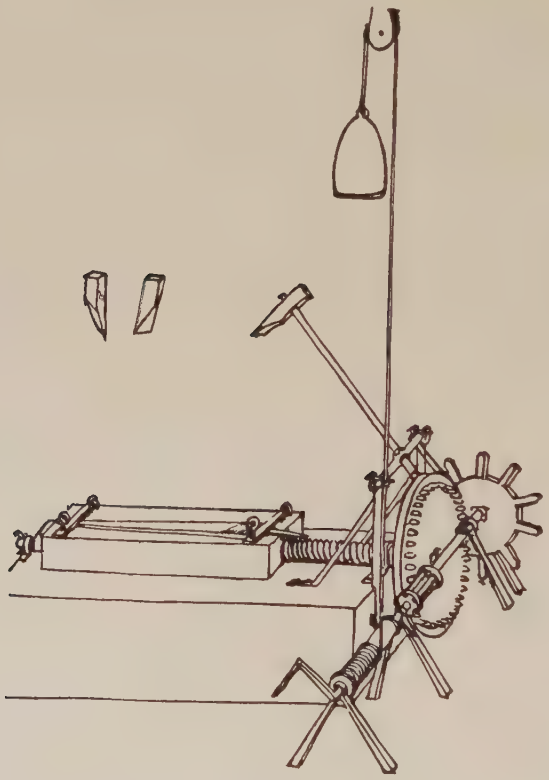


Fig. 58.—File cutter.

The various devices for cutting screws and nuts must have been brought to a higher degree of practical application. The notebooks contain sketches for four distinct sets of apparatus; two sets designed for cutting screws on wooden spindles or in wooden nuts, one piece of apparatus designed for preparing moulds for casting and polishing bronze screws. The most interesting of

these devices is shown in Figs. 59 and 60.[173] The process of cutting the nut is shown in Fig. 59. In a block *m*, a hole is made of the gross diameter of the screw. A strip of metal *ab* is nailed over one end of the hole in such fashion as to project over it by one-half the breadth of a finger. The screw *rf* must then be cut appropriately to the thread to be made in the nut, and a steel point is set in this spindle. The thread of the screw turning against the strip *ab* draws the spindle into the nut and the cutter *cd* makes the thread in the nut.

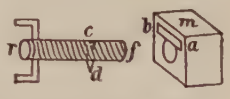


FIG. 59.—Method of cutting a screw thread in a nut.

The frame shown in Fig. 60 displays Leonardo's most notable contribution to cutting screw spindles. The spindles on the

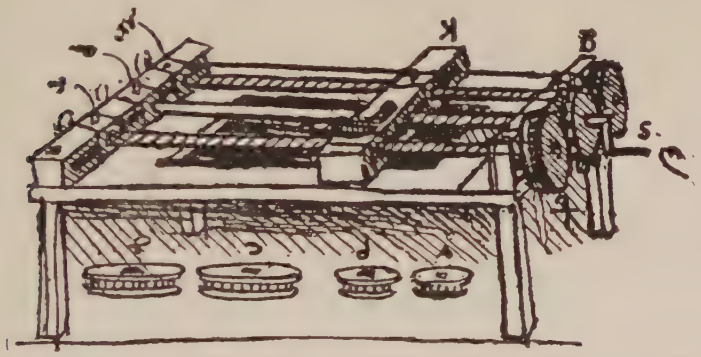


FIG. 60.—Screw cutter. (Note the reversed letters of Leonardo's mirror writing.)

outside control the movement of the cutting instrument in the moveable block towards the center of the frame. The pitch of the screw can be made identical with that of the outside screws, or made greater or less according as appropriate gears are used. Three sets are shown: one pair attached, two pairs below the table. With the larger or smaller wheels, adjustments are made in the blocks *t* and *h*, also corresponding changes in the moveable block and in the bearing block. When the operator turns the crank *m*, the cutting instrument makes a thread in the central spindle as the moveable frame is carried along the frame by the motions of the outside screws working in nuts at each end. The original drawing here reproduced correctly shows the central spindle without a thread at the left of the moveable frame; in

[173] BECK, G. M. B., p. 344; FELDHAUS, "Leonardo," p. 65.

Beck's drawing threads are incorrectly shown for the whole length of the spindle.

Feldhaus says that this "well conceived machine" stood alone for a considerable period. Other attempts were made that were clumsy and unskilful in comparison, for Leonardo's machine embodied all the essential elements of modern mechanisms for cutting long screw spindles. The provision of various gears is one of the notable indications of the quality of Leonardo's mechanical concepts. Unfortunately we are without adequate details of the influence of Leonardo's conception upon current practice. Beck infers that this apparatus was used for cutting screws in bronze or iron, and that it marks the beginning of the generalization in the use of metal screws which until this period were cast and subsequently finished with a file or cut directly from the metal with a three-cornered file. We know that metal screws of all sizes came into fairly general use in the sixteenth century, but until recently there had been little information on the development of the technique of screw cutting. Beck found other significant notices of the making of heavy screws of iron or bronze at Nurnberg by Hans Danner, who died in 1545, and his younger brother Leonard, who died in 1585. They used heavy metal screws to overthrow masonry walls. Bronze spindles were also made by them for printing presses. This Nurnberg development becomes more comprehensible if it is thought of as a perfection of a technique established by Leonardo. The slow diffusion of the new methods need hardly be a matter of surprise, though it is strange to find Besson so well acquainted with some aspects of Leonardo's work and wholly ignorant of these important devices for tool making.

Leonardo's work on the printing press is shown in Fig. 61.[174] Some of these details must represent practice then current, but an original suggestion is embodied in the notion of making the motion of the printing frame a function of the motion of the screw of the press: the downward turn is intended to draw the frame under the press, while the release of the screw is presumed to start the frame down the inclined plane indicated in the drawing. The early history of the printing press is so obscure that it is impossible to ascertain the precise relation of these sketches to the practice of Leonardo's time. The press remained a crude affair until the work of Blaew about 1620, and his improvements

[174] Beck, V. D. I., p. 567, Figs. 98–101.

won their way slowly into the practice of foreign countries. For more than a century after his time the motion of the printing frame was controlled by a hand crank such as is shown in the upper right of the figure, so it seems clear that for a long time no one succeeded in making the press as self-contained in its motions

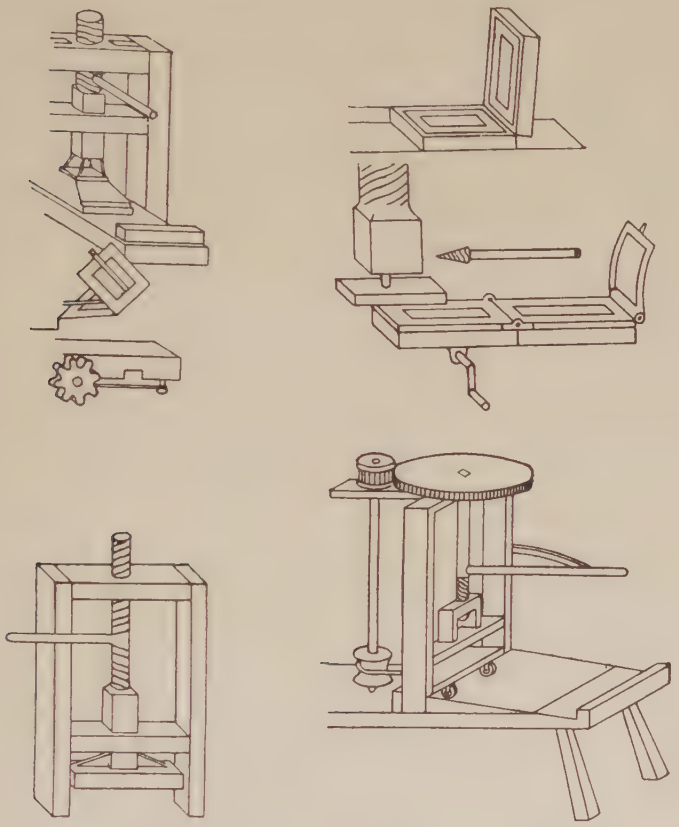


FIG. 61.—Detail of a printing press.

as Leonardo wished to. The various systems of attaching the screw spindle to the plate of the press show that Leonardo appreciated the primary technical problem of the early press: the necessity of eliminating a twisting motion in the plate.

Interesting propositions for the shaping of iron by rolls and drawing frames occur in connection with Leonardo's project for shaping iron staves for making cannon. There are sketches for a

drawing frame and for rolls, but the notes are not sufficiently detailed to make the relation of the two pieces of apparatus clear: they may be different systems for accomplishing the same objective or they may have been used at different stages in the process. For light work, both rolls and drawing benches had been in limited use since the twelfth century: both devices being mentioned in the treatise on the arts by the monk Theophilus. Leonardo was the first to propose the application of such apparatus to heavier work and it was only in the eighteenth century that rolling mills began to supplant the trip hammer for the working and shaping of iron. The problems in the development of the rolling mill were therefore matters of power and details of construction of heavy-duty apparatus that are logically secondary to the bare abstract notion of using notched and grooved rolls for the shaping of metal. The total process of achievement in this case is spread over a period of fully six centuries.

Leonardo proposed to use the rolls or the draw-bench only as a means of achieving precision in the shaping of the parts. The staves were to be worked with hammers to the approximate size desired. They were then to be put through the final processes, passing through different forms for each of the four faces of the stave. Even this modest transformation of shape would require the use of water power. Sufficient intensity of power could be secured by geared hand wheels, but the work would progress so slowly, says Leonardo, that it would not be practicable. Both devices are thus connected with horizontal water wheels of the Greek type. Other studies show that Leonardo was on the verge of converting such wheels into true turbines with appropriate modifications of the blades and an enclosing case, but some important elements of the problem do not appear explicitly in his notes.

The sketch for the drawing frame is shown in Fig. 62.[175] Many elements of detail are obscure. The rolls shown in Fig. 63[176] are more readily comprehensible, and are apparently technically adequate. The general features of the processes projected here were, in fact, applied to certain phases of metal working not more than 30 years after Leonardo's death. Our best information comes from Nurnberg and we cannot be certain of the directness of contact, but knowledge of the precise details is not essential.

[175] Beck, G. M. B., p. 430, Figs. 621–622.
[176] Beck, G. M. B., p. 432, Fig. 624.

The utilization of machinery to attain precision is further and perhaps more notably illustrated by Leonardo's projects for the improvement of the process of coinage. The old methods of

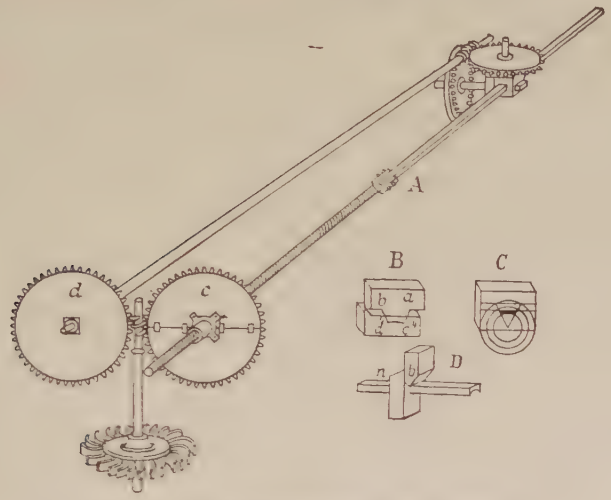


FIG. 62.—Drawing frame for metal staves.

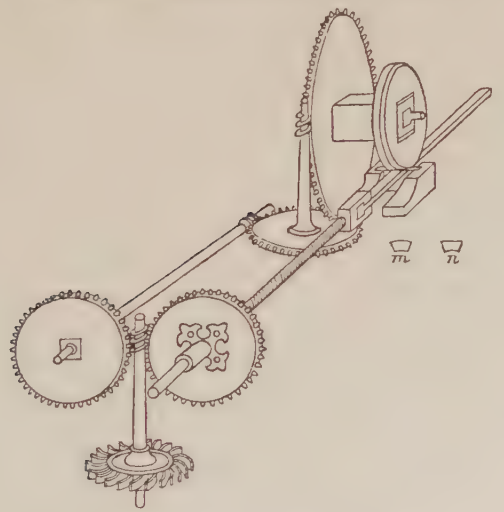


FIG. 63.—Rolls for metal working.

coinage were imperfect and unsatisfactory. It was very difficult even for the best craftsmen to turn out coins of strictly uniform weight so that wider divergences from the standard had to be

tolerated than was consistent with good monetary practice. The coins were imperfectly shaped and it was thus possible to cut them down without leaving any *prima facie* evidence of the alteration of the weight of the coins.

In the old process the metal to be coined was cast in sand to form ingots of the approximate thickness of the coins to be made. These ingots were then reheated and worked under a hammer as nearly as possible to the desired thickness. The ingots were cut into squares, which were worked under the hammer, trimmed, and weighed. The squares were then heated and formed under a hammer into circular blanks of the dimensions of the piece to be made. The blanks were passed through two successive hammerings to reduce them to the standard form. The individual blanks were also made up in rolls which were hammered in order to reduce them to sufficient uniformity to make it possible to stack them. Then, after treatment with chemicals to fix the color of the metal, the blanks were ready for the final striking under the die. Under the circumstances, the coins were far from uniform.

Leonardo proposed to simplify this process. He says:

"All the coins should be a perfect circle; and to do this a coin must before all be made perfect in weight, size, and thickness. Therefore have several plates of metal made of the same size and thickness, all drawn through the same gauge so as to come out in strips. And out of these strips you will stamp the coins, quite round as sieves are made for sorting chestnuts; and these coins can then be stamped in the way indicated above.

"The hollow of the die must be uniformly wider than the lower member, but imperceptibly.

"This cuts the coins perfectly round and of exact thickness and weight; and saves the man who cuts and weighs, and the man who makes the coins round. Hence it passes only through the hands of the gauger and of the stamper, and the coins are very superior."[177]

Although this text is directly associated only with the die forms and one of several forms of punch, the complete set of machinery involves also drawing apparatus such as occurs in other parts of the "Codice Atlantico" and also an arrangement of trip hammers to prepare the gold bars. The disorder of this assemblage of sketches is in no small measure the work of Pompeo Leoni or the binder who was charged with the task of assembling the loose sheets. There is thus a positive need of studying these various

[177] RICHTER, "Leonardo da Vinci," Vol. II, p. 18.

devices in connection with each other. There are sketches of three slightly different plans for the hammer work, the most suggestive single sketch being reproduced in Fig. 64.[178] Provision is made for seven hammers to be operated from a single driving shaft, one only of the hammers being shown in the sketch. The

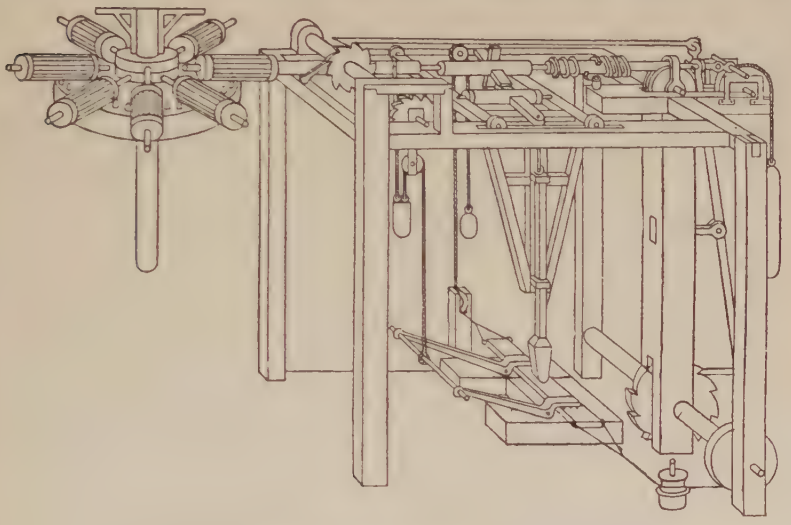


FIG. 64.—Hammer work to prepare metal for coinage.

number of variant schemes indicated the tentative character of some of the proposals and as we do not know what, if any, system was brought to trial; it is hardly necessary here to proceed to a comprehensive discussion of the mechanical details. Suffice to say that these sketches are accompanied by notes which show that they were designed to prepare just such hammered bars as would be needed for coinage. The draw-bench for these gold bars would not differ from those sketched in other places for drawing copper bands for the mirrors; or the metal staves for making cannon. Two types of punches appear: one associated in the notes with the coining frame, the other occurring elsewhere in the notes. These punches and the coining frame are shown in Figs. 65 to 69.[179] The coining frame contributes the new idea of enclosing the die in a frame or collar, so that the shaping of the coin is completely controlled, but Leonardo's device still required the use of

[178] BECK, G. M. B., p. 434, Fig. 628.

[179] BECK, G. M. B., p. 346, Figs. 487–490; p. 442, Fig. 649.

a hand hammer. The completion of the new coinage mechanism involved the development of the special form of the screw press known as the "balance." This is now attributed to Bramante, being developed by him to simplify and improve of stamping the

FIG. 65.—Punch for blank coins.

FIG. 66.—Die and collar for coining.

FIG. 67.—Die and collar for coining: closed.

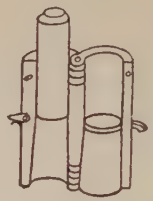


FIG. 68.—Die and collar: open.

papal seal upon the leaden bulls used to validate papal documents.

Although the introduction of the modern technique of coinage was long attributed to the goldsmiths and coiners of Augsburg and Nurnberg, it is now held that the beginnings of the new processes are to be found in Italy. We know that Leonardo was occupied

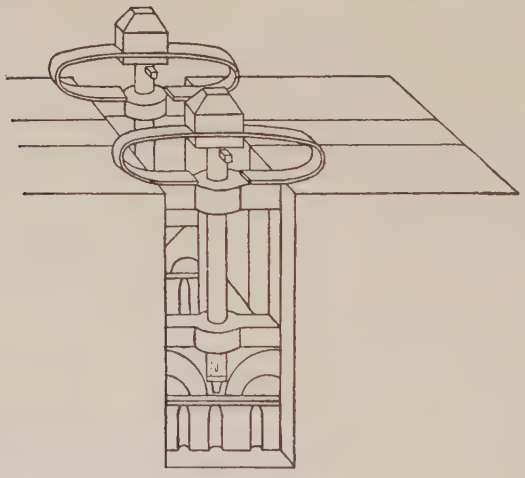


FIG. 69.—Punches.

at the papal mint during his stay in Rome, and though there is no record of any coins struck under his supervision, the work of Benvenuto Cellini is presumed to be a development of the methods suggested by Leonardo and Bramante. Cellini's coins and medals

undoubtedly represent the beginnings of a new technique, and his recommendations to Francis I were largely responsible for the improvements in coinage made by Henry II. The French ambassador at Augsburg, however, had given such enthusiastic accounts of the procedure at the mint there that the French sought their instruction in Germany rather than in Italy. The introduction of the new technique into Spain was likewise based upon the German technique. In the new process water power was applied to the rolls by which the ingots were shaped so that the new money came to be called milled money, for a water wheel was regularly described as a mill. This development was in nearly every respect a fulfilment of the concepts and purposes of Leonardo, though he seems to have misjudged the relative merits of the rolls and the drawing frame. His work thus consisted in defining the problem and elaborating the various mechanical alternatives opened up by such a new conception of the process. On this phase of invention as in so many others his work was that of the forerunner: the work of conception.

In these days of emphasis upon final achievement, mere concepts seem to be of small significance, but the most striking index of the quality of Leonardo's talents is really shown by the breadth of imagination disclosed by his concepts. These notions which carried him so far beyond the limits of immediate accomplishment were the most novel and unique feature of his career. Save for relatively isolated cases, mechanical innovation had been empirical, realistic, and practical. Achievements of great consequence had been realized, but by a process in which the immediate end was ever in the foreground. It is only with Leonardo that the process of invention is lifted decisively into the field of the imagination; it becomes a pursuit of the remote ends that are suggested by the discoveries of physical science and the consciously felt principles of mechanics. In the case of this process of coinage the actual historical record leaves no considerable gaps, so that Leonardo's contribution in that particular instance may serve as a type. He began many things that others were to finish, and in this field therefore he seldom secured the recognition that was due him. But there is certainly no ground for the view that his scientific and mechanical capacities were in any sense inferior to the artistic powers which afforded naturally a simpler and more direct claim to recognition.

Chapter VIII

THE INVENTION OF PRINTING

I

The development of printing more than any other single achievement marks the line of division between medieval and modern technology. In form and in substance, it was indicative of an epoch-making technical change. In this achievement we have the first instance of a process being pushed through to a decisive stage in a relatively short time, despite the relative remoteness of the ends to be achieved. Despite the obscurity of the records, it seems evident that the final result involved more imaginative effort and less of mere empiricism than had commonly been the case with inventions. We see here the same transfer to the field of the imagination that is clearly evident in all the work of Leonardo da Vinci. The process of accomplishment is evidently different from that involved in the development of the mechanical clock. The consequences of the achievement, too, were of commanding importance. The possibility of producing books at lower costs and of higher standards of accuracy contributed decisively to the diffusion of scientific and technical knowledge, thus intensifying the effect of the new intellectual activities and contributing an essential feature to the development of modern scholarship with its growing emphasis on written, as distinct from oral, communication and instruction. If we include in this general development, as we should, the related arts of engraving and etching, we must note the significance to cartography of the new methods of reproduction as finally perfected by the Antwerp school of the sixteenth century; a scientific accomplishment of the utmost moment to the development of commerce.

But even apart from these less direct technical consequences, the new processes are significant in themselves. Printing is one of the first instances of the substitution of mechanical devices for direct hand work in the interest of accuracy and refinement in execution as well as in the interest of reduced cost. By capitalistic

methods and mass production, a new and superior product was evolved. All the economic consequences of these inventions were thus characteristic of the new order; and even at the outset, the printing office disclosed the features of a factory enterprise rather than those of the craft shop.

The entire achievement embodied in the printed book with illustrations presents a striking case of the multiplicity of individual acts of invention that are requisite to bring about a new result. In its entirety, this accomplishment involves: the invention of paper and of inks made with an oil base; the development of engraving on wood and on metals; the development of type founding and of metal reproductions of wood blocks; the development of the press and the special technique of press work involved in printing.

The history of paper is in some ways a separate subject, but it must be evident that the generalization of printing could not have proceeded significantly with any other basic medium. Parchment is difficult to handle, costly, and narrowly limited in supply. Books would have remained an article of luxury, if parchment had been the only available medium of issue. Papyrus is hard, brittle, and unsuitable for printing. The introduction of linen paper making into Europe from China was thus an important preliminary condition. The origin of this product in the Far East, and the stages of its transfer overland to Europe are now fairly well ascertained, so that the chronology of the transfers is adequately established. Invented in central China at the close of the first century of the Christian era, its use spread rapidly within the empire and extended even to the outposts of the Chinese empire stationed on the roads to Turkestan at the edges of the Desert of Gobi. The use of the new product did not extend beyond these limits until the seventh century, but the development of both use and manufacture spread steadily thereafter. Paper was made in Samarkand as early as 751; in Bagdad, by 793; in Egypt, by 900; in Morocco, by 1100; at Jativa in Spain, by 1150; at Herault in southern France, by 1189; at Montefano, in Italy by 1276. From France and Italy the new process spread slowly northward, reaching Cologne in 1320 and Nurnberg by 1391.

Rubbings were taken in China from stone inscriptions at an early date, but there is no mention of anything worthy of the name of printing until the sixth century A.D., when prints were made from wooden blocks. The use of moveable characters made by punches

was introduced in the eleventh century, but the technique was wholly different from anything known in the West and there can scarce be any question of significant contacts, even if the introduction of playing cards could be decisively traced to Chinese influences. The Chinese episode is significant, however, as an index of the relation of the use of paper to the taking of rubbings and the making of impressions. The chronology of the use and manufacture of paper in Europe is thus worthy of note.

The development of inks is closely associated with the history of painting, for the early mediums used in printing were borrowed from the painters rather than from the calligraphers. The early prints from wood blocks were made with various thin distempers, but preparations with a base of boiled oil soon supplanted these lighter fluids. These materials, however, were developed without exclusive reference to printing. The general features of the press, too, were taken over from closely related crafts: the smaller cloth and wine presses embodied most of the features required by the printing press although various modifications were essential to the convenience of the workers and the accuracy of operation. All of these phases of the final accomplishment were in the nature of "given" data, commonly known to craftsmen for a measurable period prior to the perfection of the new art. The primary problems of innovation centered around the arts of engraving and casting, and in this connection a number of inventions and discoveries were certainly involved. Two distinct crafts were in a position to contribute to the development of the new process: the wood engravers and the goldsmiths. The goldsmiths were at that time closely identified with work on coins and medals, that called for skill in the making of dies and punches, and not infrequently they did work in casting by some of the more delicate processes.

The work of the wood engravers covered a wide range: single blocks representing various scenes, mostly of devotional character; series of blocks that were used for the preparation of small books, accompanied at times by text in manuscript, at times by text engraved on the block; and at times by text set up with moveable type. It is presumed that such type were either wood or metal types cast in matrices prepared by the use of wooden punches. Arranged in logical sequence, the work of the wood engravers presents every stage that one might expect between the making of a pictorial wood engraving and the preparation of metal type from wooden punches.

The difficulties for the historian arise from the uncertainties of date; there are no block books explicitly dated before 1470 and adherents of the Gutenberg tradition in its most extreme form assume that the entire series of block books is subsequent to the developments at Mainz. The undated block books, however, cannot be disposed of so easily. The technique of wood engraving first disclosed itself in individual prints, three of which bear the dates 1418, 1423, and 1437. The date 1418 on the print known as the Virgin of Brussels has been challenged, but is now commonly accepted. The other dates, 1423 for the Buxheim St. Christopher and 1437 for the St. Sebastian admit of no significant doubt. The blocks of the first two subjects contain a few engraved words, and on the St. Sebastian there are thirteen lines of engraved text embodying a prayer. This technique can thus be attributed with some certainty to a period definitely prior to the development of printing at Mainz. If technical similarities are recognized as competent evidence several of the well-known block books may be assigned to dates prior to 1430, and many are willing to accept such evidence despite real elements of weakness. The earliest date, however, that can be assigned with much confidence to any block book is 1440. This little work known as the "Spirituale Pomerium" consists of twelve block printed woodcuts accompanied by Ms. text: in itself therefore it is indicative of a very early stage of the block book. Its direct significance lies in two explicit statements bearing on the date of its completion. In subject matter, this book is so closely related to another block book, the "*Exercitium super Pater Noster*," that one must presume them to be the work of the same hand. The resemblance is closest in the second edition of the *Exercitium:* the volume consists of 10 sheets printed on one side only, comprising a series of illustrations accompanied in each case by a few lines of engraved text. This volume thus presents on the small scale all the features of the pure block book. Middleton-Wake presumes that the Priory of Gruenendæl produced a series of block engraved sheets and books beginning with the Virgin of Brussels and extending on through the second edition of the "*Exercitium super Pater Noster.*" The recent French work by Mortet accepts the general features of these identifications and dates, admitting the appearance of various block prints and block books in the vicinity of Brussels before 1440. Mortet presumes that activity of this general type may probably be inferred from the references to wood engravers at Ulm and Nordlin-

gen, which appear in 1428, 1439, and 1452. In Italy, the registers of one of the notaries of Venice mention payment of a sum in 1447 to Giovanni de Biaxio, an illuminator of Bologna, for having made divers blocks for the reproduction of the Latin grammar of Donatus and the Psalter. Mortet concludes that the block print is definitely prior to the appearance of any printing from moveable types, but the block book developed almost simultaneously with the early development of printing from types and maintained itself for a sensible period after the perfection of metal type.

II

The further development of printing is described in a notable passage of the "Chronicle of Cologne" (1499), which, unfortunately, is not without difficulties of interpretation. Advocates of both extreme theses appeal to this passage in support of their views, though it must be confessed that the Gutenbergians are obliged to make a number of emendations in explaining the text, whereas the Dutch claims to a preliminary stage in the invention are explicitly stated and with close attention to the context the apparent contradictions disappear. In bare literal translation the passage reads as follows:

" . . . the eternal God has out of his unfathomable wisdom brought into existence the laudable art, by which men now print books, and multiply them so greatly that every man may for himself read or hear read the way of salvation . . .

Item this most valuable art aforesaid is (*sic*) found first of all in Germany at Mainz on the Rhine. And it is a great honor for the German nation that such ingenious men are there to be found. And this came to pass about the year of our Lord, 1440 and from thence forward until 1450 is written the art was investigated and what belongs to it. And in the year of our Lord which is written 1450, there was a Golden year and men began to print and the first book that they printed was the Bible in Latin, and it was printed in a large character, such as the character with which Missel Books are now printed.

Item although the art is (*sic*) found at Mainz as aforesaid in the manner as it is now generally used, yet the first prefiguration is found in Holland out of the Donatuses which were in that very [country] printed before that time. And from and out of them was taken the beginning of the aforesaid art. And it is (*sic*) found much more masterly and subtilely than that same manner

was and the longer (it was practised) the more skilful it became . . . The first inventor of printing was a burgher at Mainz, and he was born at Strassburg, and named Johan Gutenburg. Item from Mainz. The aforesaid art came first of all to Cologne, then to Strassburg, and thereafter to Venice. The beginning and development of the aforesaid art was told me by word of mouth by the honorable man Master Ulrich Zell of Hanau, still, *anno* 1490 a printer at Cologne by whome the aforesaid art came to Cologne."[180]

It will be observed that the phrase "the aforesaid art" is used throughout in the somewhat technical sense of the art as then practiced, and that this perfected technique is contrasted explicitly in some passages and throughout by implication with an inferior technique by which the Dutch editions of the Donatuses were prepared. The Gutenbergians are obliged to assume that these Donatuses were printed from engraved wood blocks and not from moveable type, despite the fact that type-printed fragments appear in the bindings of Dutch books as early as 1471, which is fully as early as the block engraved Donatuses of proven date. Furthermore, the early wood engraving seems to be more largely identified with Flanders than with Holland. The passage thus affords a strong presumption in favor of the existence of early printing in Holland by a process technically inferior to that developed at Mainz.

Writers of the sixteenth century made more specific statements, citing Haarlem as the place in which this early Dutch printing was done and identifying the printer as Laurens Janszoon, the Coster (sacristan). Many writers have denied the existence of such a person; material has been brought to light which establishes his existence, but we are still without contemporary evidence that would decisively connect him with the early Dutch printing. The fact remains, however, that a considerable mass of early printing has been found in Holland which cannot be successfully identified with the Mainz types either in general technique of press work or in the style of the individual letters. This series of fragments includes: the so-called Abecedarium, four sheets of a prayer book for the use of students; two sheets of a copy of the Latin grammar by Donatus, in the same type; parts of twenty different editions of Donatus, eight editions of the Doctrinale, or rhymed Latin grammar by Alexander Gallus; two editions of

[180] HODGKIN, Vol. II, p. 231.

the moral precepts of Dionysius Cato; various small works by Pius II, Petrarch, Laurentius Valla, the jurist Pontanus, the doctor of medicine Saliceto; and four editions of the Speculum humanæ salvationis, with woodcut plates printed in distemper, to accompany type set text printed in ink. Many of these fragments have been recovered from the bindings of books so that they must be placed earlier than the documents into which they were bound; but apart from this indirect evidence, there is no means of dating them. Zedler, a recent student favorable to the doctrine of an independent Dutch press, holds that this mass of material represents the work of Coster over a period of about 50 years, 1435–1484. The technique embodied in these school texts and books of devotion not only gave stimulus to other German work that surpassed it ultimately, but also remained locally important for a considerable period after the perfection of printing in Mainz by Gutenberg. Despite various bases for presumptions, the statement in the Chronicle of Cologne remains the primary claim of this Dutch work to priority over the work of Gutenberg, as well as the most direct statement that stimulus was given to the Germans by the Dutch. There is nothing to indicate even the general character of the technique by which this Dutch work was produced.

There is some text material relating to the work of goldsmiths on type molding, the cutting of punches, and the preparation of matrices. Most of the material refers to the work of Gutenberg, but in 1890 items of importance were discovered at Avignon among the minutes of notaries. There are twenty-three pieces referring to agreements made between a goldsmith Procopius Waldfogel, a native of Prague, and various clients. The documents are for the years 1444–1446 and their dates are beyond possible doubt. Some of these persons he agreed to instruct in the arts of the goldsmith, others he promised to teach the art of "writing mechanically." In July 1444, he agreed to deliver "two abecedaria of steel, two iron forms, and a vise or screw, forty-eight forms of tin, and various other forms pertaining to the art of writing." Another contract refers to "twenty-seven hebrew characters," "forty-eight letters engraved on iron," and "instruments for writing mechanically in Latin."[181] These references have been much discussed, and in their anxiety to deny the implied reference to printing, some writers have suggested that a kind of typewriter must be intended. But after all the references are quite as

[181] MORTET, "*Origines et debuts de l'imprimerie*," pp. 41–42.

explicit as those in the Gutenberg documents, though we have no surviving evidence of printing at Avignon at this time. The interest of the material, however, lies not in any direct practical consequences that the work may have had, but in the evident fact of work on hard metal punches and type molds. Both Hodgkin and Mori hesitate to ascribe any early use of hard metal punches to the Dutch printer or printers or to Gutenberg, but this Bohemian goldsmith was trying out all the metals, early in the decade of the forties. For it must be noted that the document of 1444 does not refer to a process that is then new to Waldfogel, but to an art which he had already thoroughly learned. The process was tested, at least on a small scale, because we find a record in 1446 that a satisfactory test had been concluded. This is the most decisive evidence we possess that work of importance, looking towards printing, was proceeding independently in more than one center. Various lines of development were leading into this new method of reproducing books and thus work was progressing more or less simultaneously in the crafts concerned with engraving and metal founding.

The text references to Gutenberg's work are found in the legal records growing out of his partnerships at Strassburg about 1439, and in the notarial summary of proceedings at Mainz in 1455 when the partnership with Fust was finally terminated. The Strassburg documents indicate that Gutenberg was working on a variety of projects that were being financed by various partners: the only project explicitly described was for the manufacture of mirrors to be sold at the Fair at Aix-la-Chapelle. The associates in this enterprise discovered that Gutenberg was also working on other projects and in consideration of the advancement of new funds an agreement was made in 1438 that Gutenberg should reveal all his secrets and share all his ventures with his associates. It was further provided that in the event of the death of any one of the partners, the others "should at the end of five years, pay one hundred guilders to the heirs of the deceased, for all things made or unmade, for the money advanced, and for the forms and all the tools nothing excepted." Towards the end of the year Andrew Dritzehen died, and suit was brought to compel Gutenberg to return the money advanced or admit a new partner to the enterprise. The council denied the suit and ordered the maintenance of the partnership. The interest attaches chiefly to the testimony of some of the witnesses which bore upon the character of certain

apparatus. Two items are of primary importance: the testimony of Hans Dünne a goldsmith to the effect that " . . . three years ago or thereabouts he had earned from Gutenberg nearly 100 guilders, merely for that which belonged to printing:" the testimony of various witnesses to the effect that Gutenberg's servant came to the house of Andrew Dritzehen, after the death of the latter, with the request that "four pieces lying in a press" be taken from the press and separated, "so that none may know what it is." If these statements have any connection with printing, these four pieces in a press must be the parts of some kind of type mold, but many are not convinced that there is any real connection with printing. The evidence is not as explicit as the Avignon documents cited above, but it is not unreasonable to assume that Gutenberg was working on the problem of the type mold.

The notarial document of 1455, though explicit as regards the joint activities of Fust and Gutenberg in printing yields no intimation of the nature of the apparatus then used by Gutenberg so that despite the significance of the document as to the existence of a printing shop at Mainz from a date as early as 1450, it throws no light upon the nature of the invention. Consequently, the actual textual evidence merely establishes the fact of some invention in connection with printing without in any way indicating its character. Fust made two loans to Gutenberg, the first in 1450 to enable him to "prepare and make his tools." Fust also undertook to pay 300 guilders per year towards Gutenberg's maintenance and towards the wages of assistants, and the cost "of parchment, paper, ink and the like." Two years later, a second loan was granted.

The early printing at Mainz is represented by a series of items, several of which are explicitly dated, and for others dates can be assigned with considerable confidence. The fragment of an almanac can be attributed to the year 1448 on the strength of the dates assigned in the text for the various astronomical data. The 42-line Bible must be prior to 1453 as there is an illuminator's date of that year upon a copy in the museum at Leipzig. Much of this work is identified with the work of the establishment of Fust and Gutenberg, as no other independent establishment is known for the period prior to 1455. After that date, Fust associated himself with Peter Schoeffer of Gensheim who had already been employed in the shop of Fust and Gutenberg. The identification of later work thus becomes a matter of considerable difficulty.

There is evidence that Gutenberg continued to be identified with printing until his death, but little is known of the continuity or character of his work.

The production of the Psalter of 1457 by Fust and Schoeffer marks an improvement in technique over any accomplishment that can be identified with Gutenberg. The generalization of printing begins after rather than before these improvements had taken place so that the significance of the contributions of Gutenberg and Schoeffer is genuinely in doubt. Charles Enschedé following the conclusions of his ancestor of the eighteenth century took the position that Schoeffer's books would lend support to such a view and this evidence is cited by Zedler though others set little store by the colophon of the edition of Justinian's Institutes (1468) which is most important in this connection. As Fust was the capitalist rather than the technician, it was really Schoeffer who was responsible for the renown of Mainz as a center of printing.

III

There is thus text evidence of a sort and specimens of printing from moveable type that indicate decisively the presence of three stages in technical development. In the order of the earliest work in each group, these stages were successive though they follow at close intervals, and the improvements in technique were diffused so slowly that it is only towards the last decade of the fifteenth century that the methods of printing were generalized, at the level of the best practice. It is fairly clear that we have to deal with a process of development which involves a number of technological changes, any one of which must properly be classed as an invention though none of them could in propriety be described in such a general phrase as the "invention of printing" nor even in a more restricted sense as the "invention of printing from moveable type." The inconclusiveness of the long-drawn-out controversy is due in large measure to the inaccuracy of the statement of the problem and to the naïve disposition to assume that only one invention was involved. The whole matter is cogently restated by the title of the pamphlet by Mori: "What Did Gutenberg Invent?" Unfortunately, no wholly decisive answer can be given, because we really have no competent contemporary evidence as to the details of the processes by which the various early books were produced. At the same time, much light has been thrown upon

the subject by the writings of Enschedé, of Hodgkin, and of Mori, and, for the purposes of illustrating the inherent complexity of the process of invention, it is much more important to reach a sound appreciation of the scope of the problem than to arrive at positive conclusions.

From this point of view attempts to reproduce the early processes of printing are of especial moment. Work of this character was done in the eighteenth century in connection with the discussion of the possibility of making wooden type. Since the beginning of the present century experiments have been made in the production of metal type. The results emphasize the complexity of the transition from the wooden block to the accurately set page of metal type.

Johannes Enschedé (1768) was convinced that small moveable type could be produced in significant quantity only by some process of casting, and in classifying the metal types he and his descendant recognized only the possibilities presented by metal matrices. With these assumptions, it would be necessary to assume that all the early printing was done from types cast in lead matrices and that the primary improvement consisted in the transition to the copper matrices that could be prepared only with highly tempered steel punches. Such a view did not afford an adequate account of the gradation of achievement represented by the work of the early Dutch press, of Gutenberg, and of Schoeffer. The suggestion of Bernard (1853) and the recent demonstrations of Hodgkin and Mori offer possible explanations of just such gradation of achievement as is presented by the surviving remains of the earliest printing, and to that extent they provide possible answers to the problem, but the identification of these general processes with particular inventors rests largely upon "circumstantial" evidence and in history, as in court, such evidence has serious elements of weakness. The fact of gradation and the general elements of the possible gradations can be established beyond reasonable doubt.

The primary contact between wood engraving and printing from moveable metal types consists in the use of wood as the medium for making the forms from which the types were to be cast. As it seems now to be pretty well recognized that all the early forms were of wood, it is needless to discuss the question of the possibility of printing from wood type. Wood type is still used for much large-sized display work and the technique of

printing from wood and cleaning the type could present no difficulty with individual type that would not likewise be presented by a solid block. The transition from distemper to ink merely involved a new technique of cleaning. One may doubt if it would be practical to attempt to cut to type for even a small book, but such economic questions are rather dangerous in view of the number of books printed from engraved blocks in the decades of 1470–1490. Undoubtedly it would cost less to engrave the blocks than to prepare an equivalent font of moveable type, but it would likewise be possible to make more extended use of the type than of the blocks.

The essential difficulty in making moveable type of wood lies in the accurate cutting of the body of the type. Hogkin demonstrated that this difficulty need not be serious if the type face is engraved on the grain end of a block prepared for a strip of letters. After the letters have been engraved they may be divided and planed with the long grain in a shooting box so that the accuracy of the type body may be assured. The general method may be readily seen in the adjoining figure (Fig. 70).[182] As the block engravings were made on the long grain, it would be impossible to cut up a block into its individual letters and subsequently reduce the bodies of the pieces to anything approaching regularity.

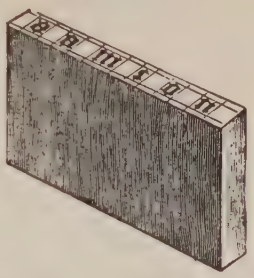


Fig. 70.—Block of wood prepared for cutting letters.

The cost of producing individual wooden letters may well have been prohibitive even for a small book and thus the notion of reproducing the wooden form in metal would be suggested. Prior to the discovery of the possibility of casting in a metal mold with metal matrices the simplest process available for such a task would be casting in sand. Modern experiments with other media are distinctly unsuccessful. Some of the plates in early books, and the large initials in Schoeffer's Psalter of 1457 show significant traces of being reproduced from models cast in sand. There are differences between the imprint at the edges and the center and small imperfections due to the withdrawal of particles of sand adhering to the wooden form. It is therefore not without explicit evidence that the process of sand casting is carried back into the

[182] Hodgkin, Vol. II, p. 45.

earlier history of type founding, and it would be of the utmost importance if wet sand were used, for that process is supposed to be of later origin. The problem of casting type in sand, however, was difficult. If an ordinary two-part casting box is used the forms would be pressed into the bottom part with only a small part of the body and the engraved end protruding. The forms being properly dusted to prevent adhesion of sand, the top would be laid on and an impression thus made of the engraved ends of

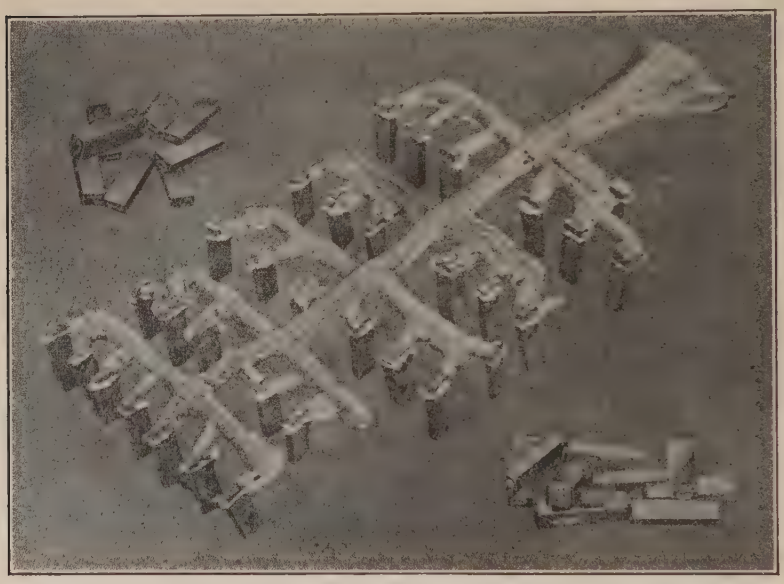


FIG. 71.—Type cast in sand.

the forms and of the remainder of the type body. The impression completed, the top of the casting box would be removed, the casting channels would be formed, and then it would be necessary to withdraw the wooden forms. This is a most delicate operation if the bodies are precisely rectangular, as it is difficult to withdraw such a form without injury to the mold. Mori, however, seemed to be wholly satisfied with his results which would produce a casting such as is shown in Fig. 71.[183] When the raw casting is cut up, the individual types would have to be finished with a file to remove the ridges formed at the junction of the two parts of the casting box. Hodgkin after experiments with such a process remained

[183] MORI, G., "*Was hat Gutenberg erfunden?*" Plate 5.

dissatisfied. Serviceable types could be produced at a slow rate without retouching of the faces, but the type bodies were irregular and rough, likely to be out of alignment with the face. Much hand work would thus be necessary to finish the type, costs would mount rapidly, and the volume of production would even then be small.

It must be remembered that the early Dutch printing was extremely defective, so much so that the arguments for the use of moveable types rested in large measure on these defects. Thus the analysis of the so-called "Abecedarium" turned largely on the presence of defects. These few sheets of parchment were discovered in 1751 by Johannes Enschedé in the covers of a breviary. They contain an alphabet and four prayers in Latin; the Pater Noster, the Ave Maria, the Credo, the Ave Salus Mundi. It was called the "Abecedarium" because it seemed to be intended for use as a reading book rather than as a devotional work. Enschedé was convinced that it was printed from metal type though his contemporaries insisted that it was printed from blocks or from moveable wooden type. A report was prepared by his best engraver, and though there may have been some bias in the latter's mind the document is interesting and the judgment is now commonly accepted. The items emphasized are: . . . "the irregularity of alignment, the unequal heighth of the letters, the mutual independence of the various characters, and the absence of any evidence of a graver's tool." There are various small defects which show decisively that the letters were cast. Both J. Enschedé and his engraver Fleishman presumed that a brass punch had been used to prepare a metal matrix. The defectiveness of sand casting would not preclude its use for the making of such type as was used in the "Abecedarium."

The full possibilities of sand casting are extremely difficult to reconstruct. Dr. Nicholaus of Berlin has recently suggested that letters might be cast in thin sheets in bronze or type metal. The metal plates might then be cut up and these moveable type set up with glutinous filling to secure exact adjustment as bookbinders still frequently do in setting up type for the impressions of titles of books.[184] This suggestion is especially interesting because it provides independent support for conjectures of Hodgkin, who presumed an attempt to meet the difficulties of casting accurate type bodies by first casting the type end separately and then

[184] *B. G. T. I.*, Vol. XI, p. 90.

subsequently casting a type body upon it in a mold made of hard metal.

Hodgkin demonstrated the possibility of casting type in two operations in this fashion, but at times the junction was not perfect; at some temperatures the type body failed to adhere to the type end, so that if such methods had been followed the discovery of the possibility of casting lead type in a lead mold would necessarily have been made in due course. This discovery must have been made in some fashion at some stage in the early development, and it must be ranked as one of the crucial steps in the development of type founding. This discovery would lead directly to the development of the metal type mold. Provision being made for the insertion of a lead matrix for the type face, the process of type casting would be much improved both as regards the technical adequacy of the result and as regards speed of operation. As the metal mold was permanent it could be operated more rapidly than a sand-casting box which required the most delicate attention for each operation. The lead matrix assured a more exact reproduction of the model and a better surface for printing. The introduction of the metal type mold opens up the possibilty of producing accurate type in large quantities and thus makes possible an improvement in the finish of printing and an enlargement in the scale of operation.

The development of the metal type mold, however, must needs have required no little critical elaboration of the original concept because the requirements of type founding involve the casting of types of various sizes in each single font of type. The capitals, various small letters, and punctuation marks require different sizes of type body so that the mold must admit of some considerable range of adjustment or a whole series of molds must be prepared for each of the various widths in each set of type. As this latter arrangement would hardly be convenient, it is not too much to presume that the decisive problem in the development of type casting was the development of an adjustable metal mold. The apparatus and the process of development will be more readily understood by the non-technical reader if the logically possible stages are reviewed briefly.

An unadjustable metal mold is shown in Fig. 72.[185] The smaller section on the right fits into the left-hand section and is secured by a clamp. The matrix is seen at the bottom of the left-hand

[185] Hodgkin, Vol. II, Plate II, Fig. 6, at p. 52.

section; it consists of an oblong piece of metal (lead) carrying the impression of the punch. The metal parts are encased in heavy covers of wood so that the mould may be held in the hand. In this instance the line of division divides the cross-section of the type body into rectangular halves. Such a design presented two difficulties: each mould would only suffice for one size of type, and on account of the mode of division the mould is not as readily cleared of the finished casting as might be desired. The attempt to meet the simpler problem might easily lead to a solution of the more difficult task. The diagrams reproduced in Fig. 73[186] illustrate this line of reasoning. The type would be more readily

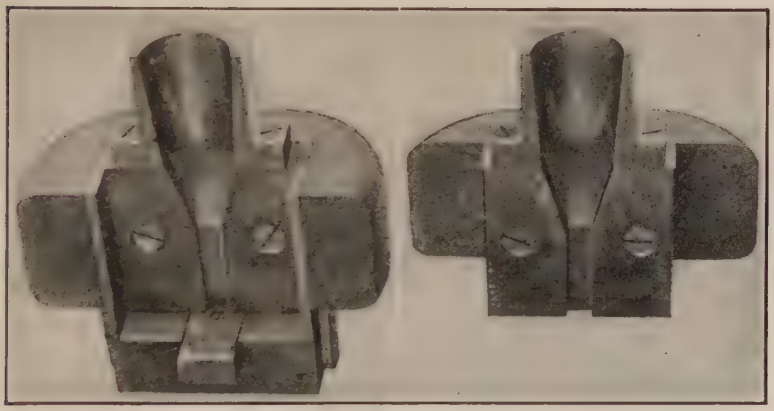


FIG. 72.—Unadjustable type mould.

cleared from a mitred mould than from the square-cut mould; but once the mould is cut into mitred sections the possibility of adjustment to varying widths of type would soon suggest itself, and with this accomplished the most serious obstacles to practical type founding would be overcome. Hodgkin insists that these comments and diagrams are merely designed to depict concretely the stages by which an inventor would be led along from attempted improvements in the process of sand casting to the discovery of the possible use of a lead matrix and thence to the development of an adjustable metal mould. The intermediate forms would in this case be represented only by a more or less protracted series of experiments by the inventor. There is every ground for presuming this to be the most important single invention in the

[186] HODGKIN, Vol. II, p. 54.

development of early printing, and the form of the mould itself underwent little improvement for a century or more. Searches made at Hodgkin's suggestion in the storehouse of the Enschedé at Haarlem brought to light the primary parts of a type mould as used about 1540. The fastenings are gone, but all the essential features are shown in Fig. 74.[187] The matrix would apparently be inserted at the bottom, being held in place by a clamp. This mould would cast a type without a "break," that is to say, with no indicated line of division between the body of the type itself and the surplus metal end, or "runner," which must be removed by a saw. After a considerable interval the edges of the funnel of the mould were made with an overhang so that the casting would indicate accurately the line at which the surplus metal should be cut off. These features are indicated in Fig. 75.[188] This improvement was introduced in the latter part of the sixteenth century. Since then, bars have been inserted to provide for the notches used in locking the type into the forms, but on the whole the hand-type mould has undergone only minor changes since its first invention.

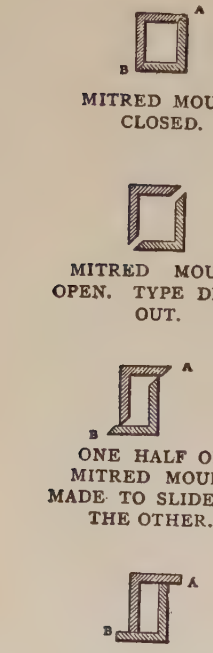


Fig. 73.—Hypothetical evolution of the adjustable type mould.

The complete technique of type casting involved not only the

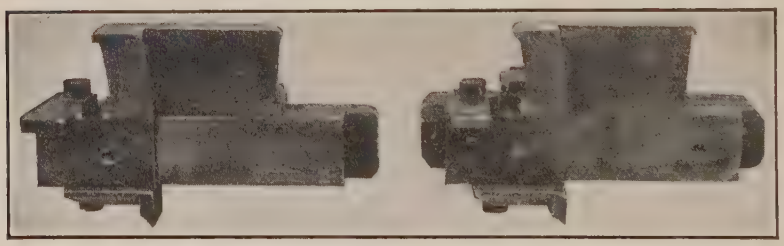


Fig. 74.—Adjustable type mould, about 1540.

development of the mould, but also the preparation of the punches and matrices. Hodgkin was successful in producing adequate

[187] Hodgkin, Vol. II, Plate IV, Fig. 1.

[188] Hodgkin, Vol. II, p. 60.

lead matrices by tapping wooden punches into cold lead, or in the case of some of the larger and more delicately formed letters tapping the matrix on the wooden form. Type of the size of the 42-line Bible was produced in this way. The type of the indulgences of 1454 and 1455 presented more difficulties. Wood engravers were loath to attempt these smaller letters and though a few wood punches were finally made with complete success, it proved more feasible to make the punches for such type out of brass. Lead matrices were still used and adequate results secured. In view of the evident experimentation of Waldfogel at Avignon with a considerable array of metals, it would seem hardly necessary to doubt the competence of a good goldsmith in the matter of producing brass punches. No technological difficulties would be encountered in preparing type of the style used in the indulgences from lead matrices, but there is, obviously, no means of establishing a significant inference as to the methods employed. Lead matrices were actually employed until after 1500, though the use of copper had begun before that time. The Enschedé have lead matrices dating from 1510, and a case of copper matrices whose punches were cut in 1490 by Henric of Delft, one of the first letter founders who cast type for sale to other printers. In general, it is commonly held that the production of the smaller fonts of type was associated with changes in the metals used as punches and as matrices, the finest results being obtained with steel punches and copper matrices. The final development of printing through a wide range of sizes of type and with refinements of form required no little development in punch cutting in the harder metals, so that this feature must be considered though it seems in many respects to be less important than the development of the type mold.

FIG. 75.—Type castings without and with "break."

The development of type founding may thus be associated with three distinct stages: the application of the process of casting in sand to the making of metal type; the invention of the adjustable metal type mold for use with lead matrices; the improvement of punches and the preparation of copper matrices. Strictly speaking, printing from moveable types begins with the use of sand-cast type, but this was not the strategic invention in the series, because the results were imperfect and the process was incapable of any

large development. With such a technique, accomplishment would be restricted to small school texts and devotional books. The results would not bear comparison with the better manuscript work and the printed book would merely have provided some cheap reading matter in a restricted circle. As the book was essentially an object of luxury, such printing would have possessed a most limited significance. The feature of the episode lies in the fact that the strategic invention occurs at a somewhat late stage in the process.

The case is not without parallel, however, for there are similarly late achievements with the steam locomotive, the steamboat, and the electric railway. In these cases, the inadequacy of the earlier results was so serious that the general public has given little attention to the accomplishments that antedate the strategic invention by which the new procedure was definitely established as a part of the general technique of social life. In these cases, however, the various accomplishments are so explicitly recorded that no serious historical doubts can be raised. The ambiguities of the explicit records have complicated matters seriously in the history of printing and type founding. The texts and the circumstantial evidence must be handled very arbitrarily if the first work of the early Dutch press is not placed prior to 1440 or 1445. It is especially difficult to evade the conclusions that would normally be drawn from the entries in the diary of the Abbot of Cambrai which imply no little activity in printing prior to 1445. As the earliest provable date of Mainz printing is 1447–1448, and no actual early printing is provable at Strassburg, there is independent confirmation of the literal interpretation of the account given in the chronicle of Cologne. It is then reasonable, on the strength of purely circumstantial evidence, to identify the process of casting type in sand with the work of the early Dutch press. Any attempt to identify the printer or printers or their location would carry us beyond competent historical evidence.

We are thus brought to the question propounded by Mori, What did Gutenberg invent? If evidence of all classes be frankly considered, it is difficult to find any answer other than that proposed by Hodgkin, Mori, and their predecessors in technological inquiry. The text evidence is wholly inconclusive, but one of the two early Bibles must certainly be attributed to the critical period of Gutenberg's work between the years 1447 and 1455. Even Mortet who is disinclined to credit Gutenberg with the invention

of the type mold, grants him the 36-line Bible, apparently without appreciating the implications, for the printing of the Bible is the most decisive circumstantial evidence we have of the date of the adjustable type mold. Without such an instrument the casting of the type would be practically impossible. The Almanac and the Donatus may be regarded as test work associated with the development of the complete technical procedure that must be associated with the achievement of the adjustable mold. How early the mold was available we cannot say, but we are certainly entitled to say that it cannot be later than the work on the Bible. As the best opinion seems to favor the recognition of the 42-line Bible as the earlier of the two, we may place the perfection of the type mold at least as much before 1453 as the work on the Bible would require. From this time on the printing of large books in luxurious style grew steadily, and thus there is every possible objective evidence of the decisive character of the changes introduced by Gutenberg at Mainz.

Whether Gutenberg himself took the next steps or whether the improvements in punches and matrices was the independent work of Schoeffer are questions that do not yield to the kind of circumstantial evidence that is now alone available. We are inadequately informed of the relations between Gutenberg and Schoeffer prior to 1455 and similarly without information as to the disposal of the types and apparatus in the joint possession of Fust and Gutenberg in 1455. It is thus difficult to feel confident of the attribution to Schoeffer individually of the decisive work on punch and matrix making which gave such distinctive character to the work put out by Fust and Schoeffer and later by Schoeffer alone.

The details of the press play but a small part in the early history of printing. The earliest dated representation is of 1499, being a woodcut in a book published at Lyons on the popular medieval subject of the Dance of Death. The illustration is lacking in details, but it permits us to identify the primary features of the press and warrants the belief that the press changed little in the next two or three generations. The sketches of Leonardo da Vinci, noted herein, though possibly somewhat later in date, throw more light on the details of the press than any of the illustrations prior to 1548. The cut shown in Fig. 76 portrays the press at the moment of removing a finished sheet.[189] The mechanical

[189] "*Tijdschrift vor Boek en Bibliotheekswesen*," p. 213, Plate IX, 1906.

details do not differ significantly from those suggested in the plates of the close of the fifteenth century. The press had thus acquired a stable form prior to any complete description that has come down to us, and, as far as we can judge, no mechanical contrivances of any complexity were involved. The cloth press or small

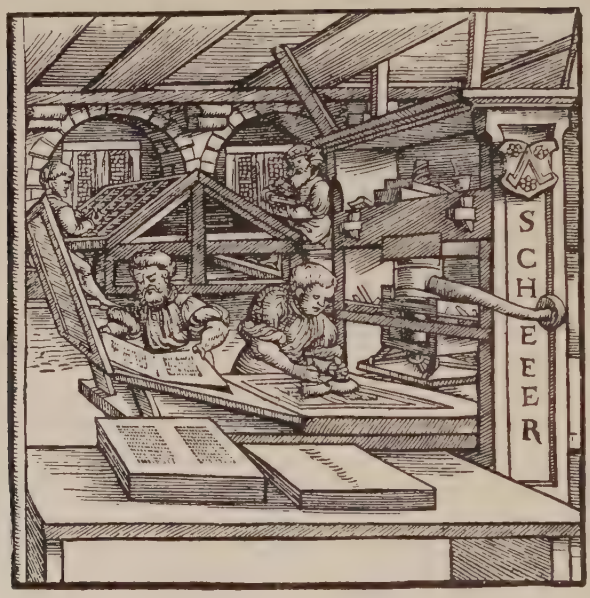


Fig. 76.—Early printing press.

wine press would furnish most of the essential parts, as that it only remained to develop appliances for holding the type and the paper and setting them appropriately into the press. These appliances must have developed rapidly during the years 1440–1455. The development of special mechanical features did not begin until Blaew in the early seventeenth century introduced refinements which mark the beginnings of a notable series of improvements in the hand press.

Chapter IX

MACHINERY OF THE TEXTILE INDUSTRIES: 300–1800

I

The early part of the Christian era was made notable in the textile industries by the completion of the development of the loom. Our information is meager and no details are certain, but the outstanding facts scarce admit of doubt. The development of the loom with pedals, if not already complete in Egypt and in Asia Minor, was completed at an early date independently or with some final stimulus from India and the Far East. The draw loom, representing the final major development in hand-loom weaving, came into use in the Near East at some time prior to the fourth century A.D., either as a local invention or through contact with the Far East. But in the case of the draw loom the grounds for presuming the existence of Oriental influences are stronger than in the the case of the loom with pedals. The figured fabrics made on the draw loom were almost exclusively silk, and the dependence of the silk trade upon far-eastern contacts increases the likelihood of actual influence. At all events, the development of the silk industry is closely associated with the notable technical development of the entire group of textile trades in this period.

Some manufacture of silk goods developed in India and in Asia Minor prior to the introduction of the mulberry-feeding silkworm from China. Filaments of silk are formed into cocoons by a considerable number of moths indigenous to the forests of India and Asia Minor, and, though these moths were never domesticated, considerable quantities of silk were gathered in the forests. The product presents a number of special problems. The cocoons were gathered after the emergence of the larvæ, so that the filaments were severed and could not be unreeled as a long, continuous thread. To be utilized at all they had to be spun, and as they lacked the properties essential to a firm spun yarn they were too fragile for anything but essentially decorative uses. Furthermore, these wild silks are difficult to dye except in a limited range of dark

colors. Though generically similar to the Chinese silks these wild silks are in fact a different product. On the authority of Aristotle, the beginnings of the silk industries of Asia Minor are to be found in the manufacture of these wild silks, commonly identified with the island of Cos. The industry subsequently extended to many parts of the mainland. Unfortunately, we have no knowledge of the technique of weaving in this section. Upon these foundations were built the more considerable industry fostered by contact with China. The use of silk developed considerably during the first centuries of the Christian era, and in the sixth century, the mulberry-feeding silkworm was successfully smuggled out of China by two Nestorian monks and brought at the instance of Justinian to Constantinople.

The period prior to the domestication of the mulberry-feeding silkworm is thus the critical period in the history of the silk industry of Asia Minor and the West and probably the period in which the first technical transformations took place in Asia Minor and in Egypt. Theodoret, Bishop of Cyr, refers to weaving figured woolen goods in Syria in the fourth century by drawing cords. This is presumed to be a reference to the draw loom, but we have no samples of such work in wool. Specimens of draw-loom work in silk are extant that are dated from the fifth and sixth centuries, and many of the textiles of this early period have not been studied with reference to the technique of weaving, so that the archæological resources at our command are by no means exhausted. It must be remembered that most of our early material comes from Egypt and as Egypt was not the early home of the silk industry the dates implicit in the Egyptian materials can hardly be assumed to represent the beginnings of the newer technique. The draw loom can thus be assumed to have been in use as early as the fourth century. All specimens of draw-loom work now known are of silk.

The relation of the silk industry to the development of the loom with pedals is not certain. None of the weave patterns not produced on a draw loom were long confined to the silk industry, but it seems likely that the serges and the equally large family of satins and damasks were at first identified with the silk industry. The production of these weave patterns might be possible even with the primitive loom, but the development of such types of goods would certainly afford incentives to the perfection of the loom. In modern times, the silk weavers of Tunis regularly use a loom with pedals, whereas the woolen weavers of the same region use

the cruder instrument without pedals or reed that we have termed the "primitive loom." The new types of fabrics would thus lead naturally to improvements in the loom and the extension of the innovations might well proceed slowly to the other textile industries. There are notable specimens of silk serges found in Egypt which are unquestionably prior to the eighth century and probably as early as the fifth century. There seems little reason to suppose that these weave patterns developed later than the figured work done on the draw loom, so that we can probably regard the initial technological development as complete by the sixth century, and sensibly earlier than that in its inception.

The development of the Byzantine period, important as it was, did not bring to an end the period of technical advance. The imperial monopoly restricted the spread of the industry and confined it to the production of the types established in the early part of the period. New influences were brought to bear upon the industry by the development of Persia under the Sassanid dynasty beginning in the fourth century, and these tendencies became the basis for a notable development with the rise of Arab power under Mohammed and his successors. Consumption was increased largely, and the industry was diffused rapidly through various new industrial regions. The types of fabrics were extended by the development of the satins and velvets and new processes for making gold thread. The technique of the industry was raised to a high level. The superiority of the Mohammedan silks was not challenged by any of the Christian centers of production until the fourteenth century, and for that reason the early history of the industry in the Mediterranean is obscured and a revival of the industry in the Byzantine Empire is in no small measure eclipsed by the renown of the Moslem products. There are isolated references to silk weavers at Rome and at Lucca in the eighth century, and at Lucca there is some documentary evidence of the continuance of the industry through the ninth and tenth centuries. Silks were made on Venetian and Genoese account at various points in the Near East as early as the eleventh century, so that considerable intimacy of contact with the manufacture must be presumed prior to the introduction of elements of the Arabic technique by way of Palermo after the Norman conquests of Sicily and Calabria. In the thirteenth century, mechanical improvements were made by the Italians in the processes of reeling and twisting. Eighteenth-century Italian treatises on

the silk industry credit one Borghesano of Bologna with the invention in 1272 of a process of reeling which was successfully kept as a trade secret at Bologna until 1538. A mechanical process of twisting was also alleged to have been invented at Bologna at about the same time. There are no intimations of any development in the loom and its harness. These Italian inventions probably mark the beginning of the western contribution to the technique of the silk industry.

The development of the worsted weaves seems to be the result of the adoption by woolen weavers of patterns at first confined to the silk industry. It is now well established that the various serge effects were first achieved in silks as had long been supposed on the basis of philological evidence. But there is no evidence of the date of the new developments in the industries based on wool, nor of the region in which the transfer of technique first took place. The innovation was probably of early date; for tiretaines and serges of wool were made in Northern France, at Caen and at Rheims early in the thirteenth century. Striped effects, which were also first executed in silks, were common among the woolens and worsteds of the thirteenth century. Meagerness of documentary evidence makes it impossible to date these changes with any success, but it is obvious that the technical development of the group of textile trades was most important in that period which yields the least documentary evidence, so that the industries that we find in the eleventh and twelfth centuries represent the completion of a long and complex evolution that had been actively in process since the beginning of the Christian era. During this long period, the primary machines and all the primary types of product were invented or brought into the Near East and later adopted in Europe.

The elements of the early state of the loom with pedals are best presented in a schematic form in which all incidental fittings are omitted. The modern drawing reproduced in Fig. 77,[190] shows the primary parts of such a loom in their simplest forms, and neither the Chinese drawings of 1210 A.D. nor the illustrations of fourteenth century European manuscripts would justify us in

[190] BARLOW, p. 78. A plate of a loom that might be interpreted as a loom with pedals is frequently attributed to a fourth-century Ms. of Virgil in the Vatican Library. A critical discussion of the Ms. and of the seventeenth-century plates frequently reproduced with it is to be found in Roth, "Primitive Looms," pp. 121–123.

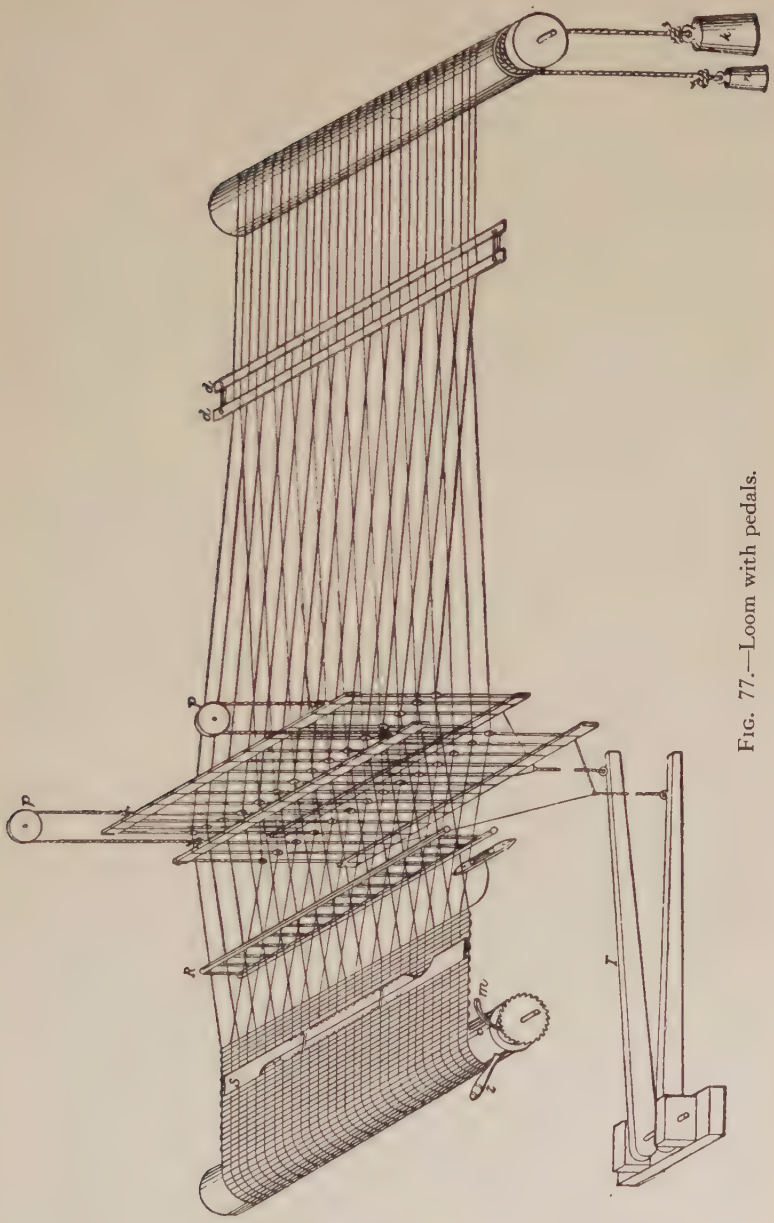


Fig. 77.—Loom with pedals.

assuming the early loom to have been developed beyond this point. The only element in the figure not certainly employed from an early date is the temple shown at *S*. This device was employed to prevent the cloth from being contracted in width during the process of weaving. In hand weaving, such a device was seldom used, and there is no ground for assuming it to be an early invention. With the advent of power weaving the temple became well-nigh indispensable, and though attempts were made to contrive a self-acting temple that would automatically change its position on the finished web, little success was achieved for a considerable period and the device shown above continued in use for a generation or more after the introduction of the power loom.

The primary loom beams and the laze rods *dd* do not differ in form or function from the corresponding parts of the Egyptian loom already shown. The heddles, however, are wholly different. They consist of light frames strung with cord. The threads of the warp pass through the eyes in the heddle cords in the sequences required by the pattern. The entire construction of these heddles marks a notable progress beyond the technique embodied in the early Egyptian loom. The warp is more definitely controlled by the harness of the loom, and as the heddle frames are worked by the pedals the weaver is free to employ his hands in the other work of the loom. The pair of heddles shown are controlled by the pedals and by the attachment to each other; consequently the drawing down of one by the pressure of the pedal, raises the other and thus opens the warp to the full width. The shuttle is passed through the portion of the open warp or shed in front of the reed *R*.

The development of the reed is one of the conspicuous features of the horizontal loom for though it can be applied to a vertical loom its use is not without inconvenience and it does not develop the supplementary functions that ultimately appear in the horizontal loom. The discovery of reeds of sound design in the Coptic tombs of Egypt[191] undoubtedly affords contributary evidence of significance to the hypothesis of important developments in the loom early in the Christian era, for such reeds must be presumed to have been used with a developed horizontal loom.

The reed shown in the diagram would be attached to the loom frame by a light cord, such as is indicated in all the early drawings of the fourteenth century. Its functions are to maintain the

[191] Roth, "Egyptian and Greek Looms," p. 22.

FIG. 78.—Chinese looms, 1210 A.D.: above, plain loom; below, draw loom.

spacing of the warp threads and to beat up the weft into the finished web. In later forms of the loom, the reed is set in a frame which is developed so as to provide a runway for the shuttle, thus relieving the threads of the warp of the weight of the shuttle. This development of the reed frame is probably subsequent to the fourteenth century. The general features of this arrangement are shown in the diagrams of the flying shuttle.

The plain loom may be developed somewhat by the addition of more heddles so that the various simple pattern effects may be created, but the elaborate figured patterns that dominate the finer textiles can be produced only upon the draw loom, whose invention is characterized by Hooper as:

". . . the most important in the whole history of textile development. All the finest pattern weaving of the Eastern, as of the Western world, ancient and modern, has been done on the draw-loom principle, and even the invention of the Jacquard machine, which is often supposed to have supplanted it, did not alter the essential principle of draw-loom weaving in the least."[192]

The earliest pictorial representation of the draw loom appears in the Chinese work on agriculture and the silk manufacture that was completed about 1210 A.D. Figured fabrics had been woven in China since the period of feudal anarchy extending from the ninth to the third centuries B.C. We are thus unable to hazard any conjectures as to the date at which this notable loom achieved a stable form, but the general history of the silk industry shows that the pictorial material affords no clue to the dates of the inventions. The Chinese drawing is reproduced in Fig. 78.[193] This drawing admits of decisive identification of the apparatus, but it is not sufficiently detailed to disclose the principles of operation, which are shown in schematic form in Fig. 79,[194] and as we really have no knowledge of the stages of the actual development it is hardly possible to go beyond the bare statement of primary principles of the loom in its early modern form. The figure represents the loom as perfected in the seventeenth century by Dangon.

The essential feature of the draw loom lies in the fact that each thread of the warp is controlled by an individual leash. The elements of any particular pattern admit of some simplification

[192] HOOPER, "Handloom Weaving," p. 252.

[193] Anonymous "The History of Silk, Cotton, Linen, Wool, etc." New York, 1845. Frontispiece.

[194] HOOPER, "Handloom Weaving," p. 259, Fig. 105.

in the ultimate control of these individual leashes, for all the threads to be lifted for a single throw of the shuttle may be raised at one time. The repetition of a pattern thus reduces the number of combinations required. In the figure, the arrangements

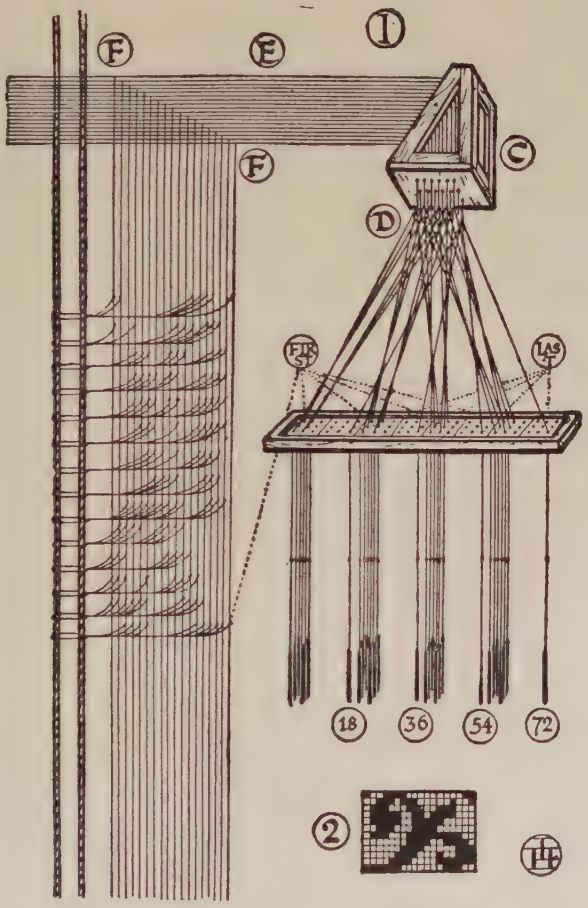


FIG. 79.—The draw loom, seventeenth century.

provide for the production of the pattern plotted in Fig. 79, at the lower right-hand corner; 72 warp threads are involved, but the motions required can be controlled by 18 pulley cords in the pulley box *C*. These 18 cords, known as tail cords, pass over pulleys which are not shown in the diagram and are carried horizontally to an adjoining wall where they are securely fastened: the 18

cords are represented schematically by the lines *E*. Attached to each of these cords at a series of points *F* is a series of cords that hang vertically, these are known as the simple. In front of these cords of the simple are two heavy guide cords, to which are attached cords which connect the cords of the simple that must be drawn for each line of weft. The guide cords thus serve to keep the ties in regular order, free from entanglement. The weaver's assistant by drawing the cords of the simple forward and downward raised the appropriate leashes to open the warp. In damask weaving, these cords must needs be held for three or four shoots of weft. On account of the number of threads involved the task required considerable strength. Thus, a fabric calling for 28 repeats of the pattern shown above, assuming weights of 1 ounce each on the leashes, would require a pull of 36 pounds for the heaviest lines in the design. Economy of physical effort as well as economy of labor inspired various mechanical improvements in the loom, long before it became automatic.

II

The application of mechanism to the process of spinning also takes place just prior to beginnings of any adequate record of the technique of the textile industries, but, in this instance, we have important clues which have been largely neglected. Good weaving requires an orderly winding of the bobbin or quill that is set in the shuttle, and it seems almost certain that the first applications of mechanism in the preparation of yarn was restricted to this subsidiary process of quilling.

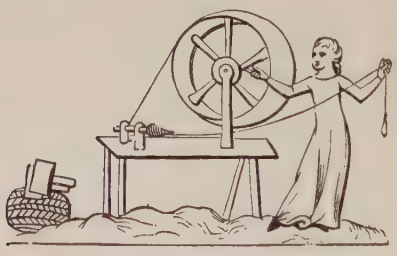


Fig. 80.—The quilling wheel.

In the early form of the wheel there is a spindle but no flyer. One of two fourteenth-century illustrations of the wheel in use is reproduced in Fig. 80.[195] In this case the woman seems to be winding the finished yarn from the loose spindle to the quill for the shuttle. There is an illumination of about the same date in a volume containing the statutes of the weavers of blue cloth

[195] Rock, "Textile Fabrics," p. 48, lower figure. See also, Horner, "Linen Trade of Europe," p. 8.

at Ypres, and in this one of the weaver's assistants is shown winding quills from a skein set on a reeling frame. Unfortunately, the plate does not lend itself to photographic reproduction. The other early illustrations we have are of this same wheel, carrying the spindle, but no flyer. There is a long series of illustrations of spinning with the distaff and loose spindle extending from 1169 down to the sixteenth and seventeenth centuries, and we know that this simplest method of hand spinning continued in substantial use down to the late eighteenth century in many important textile centers of Europe. While it is possible to use the quilling wheel for spinning, there are certainly strong grounds for presuming that spinning was not the principal nor the original use of this early form of the wheel. The origin of this wheel is not known. Modern survivals indicate that it is of Oriental origin, and Reuleaux believes that it made its way to the western world during the period of Roman domination of the Near East. Mechanically it is a device of great interest because it is one of the earliest instances of an attempt to utilize continuous rotary motion.

Positive evidence of the use of the wheel for spinning appears at Speier in 1298, in the provision that wheel-spun yarn may be used for the weft but not for the warp.[196] Similar evidence is available to indicate such use of the wheel in other sections of Germany at early dates but no attempt has been made to work out an adequate chronology of these technical developments.

Reference has already been made to the early development of the fulling mill driven by water power. References appear in the Domesday survey and are abundant in England from the latter part of the twelfth century. Apparently, the diffusion of this appliance was somewhat capricious, for the older process of treading the cloth in vats did not pass out of use until the latter part of the medieval period. There are no drawings of the fulling mill prior to the Italian treatises on mills and machinery, so that we have no means of judging the mechanical competence exhibited by the early machines of this type. The principle involved was simple, but at least three general designs of fulling mills appeared in Europe and we cannot now work out the details of the development. One of the earliest plates is reproduced from Zonca's

[196] MONE, "*Zunftordnungen einzelner Handwerker*," *Zeitschrift für die Geschichte des Oberrheins*, Vol. 15, p. 281.

treatise (1607) (Fig. 81).[197] The two heavy wooden hammers are lifted by cams on the shaft turned by the water wheel. As the cam passes the head of the hammer, the hammer is released and delivers a blow to the cloth in the tank. By the sixteenth century these fulling mills were also used as washing machines, and the fuller filled in spare hours doing the village washing.

There can be no doubt that the economy of effort was considerable, and Schmoller attempted to deduce from the changes in the numbers of fullers and weavers the extent to which labor

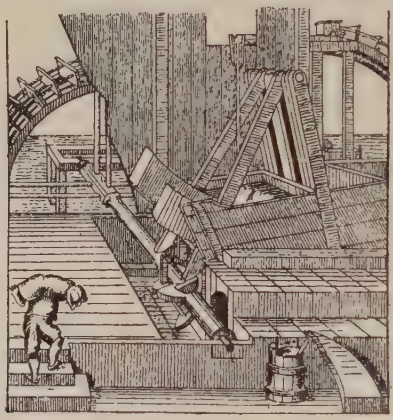


Fig. 81.—Fulling mill; Zonca, 1607.

was saved by this early application of power. Unfortunately the enumerations of fullers and weavers are too incomplete to warrant drawing conclusions. Schmoller believed that in the early period the number of fullers working without machinery was considerably in excess of the numbers of weavers; whereas one fuller working at a mill would be able to finish the product of 40 to 60 weavers. These proportions seem excessive. There is certainly no sound basis for supposing that more fullers would be required than weavers in the manufacture and processing of a given quantity of cloth. But such measures of the importance of the fulling mill fail, because some of the gain in efficiency was absorbed by an increase in the amount of finishing done. In the earlier period much cloth was used about as it came from the loom; as the medieval technique improved, more and more of the cloth was finished with some considerable care, either in the region of its manufacture or elsewhere. In many instances, the finishing

[197] Beck, G. M. B., p. 299, Fig. 362.

processes were highly concentrated and cloth was brought in substantial quantity from distant centers of production. No doubt, the development of the fulling mill played a commanding part in the improvements in the quality of the woolen goods of the medieval period.

The technique of the textile industries of Europe in the Middle Ages thus largely represents the perfection and development of machines and devices which were invented independently or brought into Europe from the Near East at various dates in the first thousand years of the Christian era. The fulling mill and the Italian inventions in silk reeling and twisting were the only inventions of the western regions during the Middle Ages. The considerable western achievements in these industries begin in the latter half of the fifteenth century with the work of Leonardo da Vinci and his contemporaries.

III

The notebooks of Leonardo contain sketches which indicate a deliberate attempt to contrive power machinery to perform most of the essential operations of the textile industries. There are sketches for silk reeling and twisting machinery; gig mills to raise the nap on woolen cloth or felt hats; plans for a shearing engine for cloth and for felt hats; and incomplete sketches for a power loom. None of the sketches explicitly show the prime mover, but a large toothed wheel is shown in most cases and the scale of the plans of many of the machines makes it evident that a considerable source of power was contemplated, either water power or a sensibly equivalent horse-driven winch. Only one of the spinning machines is explicitly shown as a hand-machine. This great project was in many respects premature. The mechanical problems involved could not be solved adequately in many instances, and probably the economic conditions in the industry would not at that time have justified the necessary outlay in experiments.

Nevertheless, some of these attempts were probably significant for the immediate development of these industries. The application of water power to silk reeling and twisting was prior to or associated with Leonardo's work: though we are in no position to know whether his sketches are a record of what others were doing, or original concepts which became the basis of the technique recorded in the treatises of the late sixteenth and early

seventeenth centuries. The flyer of Leonardo's proposed spindles must certainly be associated with the basic improvement of the quilling spindle that finally emerges as the spinning wheel driven by foot power and equipped with the flyer in its simplified form without the automatic spooling motion. The shearing engine and the loom, despite elements of interest, were too defective to have any immediate results. The breadth of conception underlying these projects of Leonardo is indicative of the vigor of his imagination. It is projects of this magnitude that mark the opening up of invention as a conscious reaching forward to distant objectives in which the immediate possibilities are forgotten and the attention concentrated on the complete realization of the abstract principle. Much certainty of judgment is shown by Leonardo's note under the sketch for the power loom.

"This is second only to the printing press in importance; no less useful in its practical application; a lucrative, beautiful, and subtle invention."[198]

Leonardo was evidently fully conscious of the importance of this group of mechanical problems which were destined to occupy technicians for nearly five hundred years, if we carry the development to the full achievement of the power loom, the wool-combing machines, ring spinning frames, and the inventions in the silk industry.

The spindle with its building motion was the most complete and original achievement of Leonardo in this field. His primary principle is shown in Fig. 82.[199] The spindle shaft *2A-2B* is supported horizontally by appropriate bearings *CC* and *DD*. The flyer 1, is securely fixed to the spindle shaft which is driven by a cord passed around the pulley wheel 3. The bobbin, mounted on a hollow axis that is fitted over the spindle shaft, is driven by the somewhat larger pulley wheel 4. By proper arrangement of the driving wheels the spindle and the bobbin can be made to revolve at different speeds, so that the flyer can be made to revolve faster or slower than the bobbin. It is not possible to judge Leonardo's intentions as to the detail of the winding motions. In order to build the yarn or thread in even layers on the bobbin the spindle with its fixed flyer is given a reciprocating motion by the movement of the fork 7. The end of the flyer is thus successively moved up

[198] Beck, V. D. I., p. 645, Fig. 117.

[199] Hooper, "The Loom and Spindle," *J. R. S. A.*, Vol. 60, p. 965, Fig. 22. See also, Beck, G. M. B., p. 108, Fig. 122.

and down the length of the bobbin at a speed proportionate to the speed of winding. All these spindles are shown in a horizontal position, although Leonardo was conscious of the frictional differences of rotating spindles in the various positions, and appreciated the advantages of the vertical position, but the vertical position presents added difficulties in dealing with the building motion. Unfortunately, some reproductions of Leonardo's notes incorrectly represent the spindles as vertical.

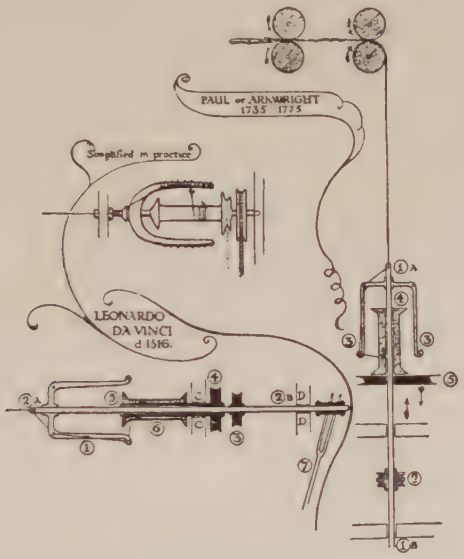


FIG. 82.—The spindle and its development.

Beck presumes that these spindles were designed for use with silk rather than wool or cotton, and that would, of course, explain the neglect of the drawing-out problem presented by all the spun fibers. The silk filaments are subjected to a process of doubling and twisting, but there is no drawing out at any stage, consequently a difficult and complex problem of mechanical treatment of wool, cotton, or flax is not present in the case of silk and as a result the application of water power to the preparation of silk took place much earlier than in the other branches of the textile industry. Most of the primary elements of silk reeling and twisting are embodied in Leonardo's sketches, but there are substantial differences between these proposals and the machines as they finally become established towards the end of the sixteenth century. The

shape of Leonardo's flyer finds closer parallels in the flyers of the spinning wheels used in the other branches of the textile industry, so that it is possible that Leonardo's work represents an intermediate stage, embodying a transfer of technical innovations from silk to the other textiles.

One of Leonardo's sketches provides for four spindles (two being shown in a sketch of one-half the complete machine) to be driven by some prime mover not shown: the arrangement could easily have been extended to carry a considerable number of spindles, and we may thus conclude that Leonardo was definitely concerned with the application of power to spinning or, rather, to silk twisting.

The only other name we have in connection with these early developments in spinning is that of Johann Jürgen, a wood carver of Wattenbüttel in Brunswick, who is commonly credited with the invention of the spinning wheel with flyer driven by foot power.[200] Jürgen's invention is commonly dated as of 1530, and as Leonardo's earliest spindle and flyer dates from about 1490 there is every reason to believe that Jürgen's work was not without antecedents in Germany or in Italy. Jürgen's spindle had no automatic building motion. The general principle is shown in the upper left of Fig. 82. Flyer and spindle are driven at different speeds by cords passing around the pulley wheels. The arms of the flyer are provided with a series of little hooks over which the finished yarn is passed: as the yarn is built up on the bobbin or spool, the spinner must stop the flyer and move the yarn up to the hook next above, and so in succession up and down. The drawing out required was produced by a movement of the hand. The distaff was still used to hold the combed or corded fiber, either separate or attached to the frame of the wheel. The most important innovation was the pedal for the application of foot power. Although such a machine was relatively simple it increased the output of the spinner to more than double the achievement possible with the earlier wheel without the flyer. With the matured spindle and flyer, spinning became practically continuous, and both winding and twisting were performed by machinery. On the simple quilling wheel, winding and twisting were largely done by machinery, but were necessarily alternative processes. A length of yarn would be spun, by a motion of the spindle in one

[200] HORNER, "Linen Trade of Europe," p. 11; FELDHAUS, "Leonardo," pp. 154–155.

direction, and then reeled by a reversal of the motion of the spindle. By making the process continuous the output would be approximately doubled. By what measure the output of the loose spindle was increased we do not know. There was also some improvement in the quality of the yarn because the attention of the spinner could be concentrated on a portion of the process. The history of the diffusion of the foot-power wheel throughout Europe is not known with any accuracy, but the improved wheel was slow in penetrating many important textile areas.

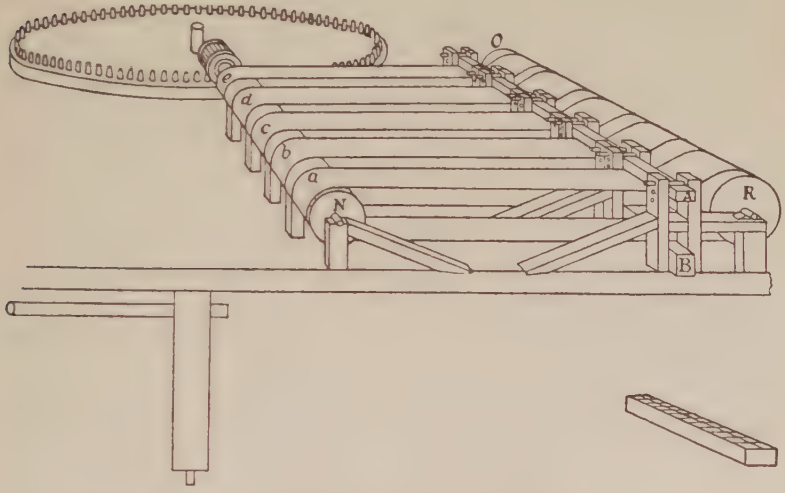


FIG. 83.—Leonardo's gig mill.

The larger of Leonardo's gig mills is shown in Fig. 83.[201] Another sketch of a smaller machine to be worked by hand power contains many interesting features, but the sketch shows only a side elevation and is not so easily understood. The figure shown implies that the apparatus is to be turned by a horse working a winch on the floor below. The lengths of cloth pass over two rollers, one of which is driven by power. The cloth is drawn under a beam *A* in which the teazles are set. In both of Leonardo's machines, the teazles were rigid; in the developed machine as shown by Zonca (1607) the teazles were carried on a roller over which the cloth passed.[202] Zonca's arrangements do not seem to be very good in detail, but it is difficult to distinguish between

[201] BECK, G. M. B., p. 456, Figs. 692–693.
[202] BECK, G. M. B., p. 314, Fig. 377.

defects of draughtmanship and defects in the design of the machine. It is at all events certain that the machine was established in its primary elements in the course of the sixteenth century, and came into use on the continent. Zonca's machine provided only for one piece of cloth and was worked by hand power. The net accomplishment was thus considerably more restricted in scope than the projects embodied in Leonardo's sketches.

There is a sketch for a power loom in the notebooks, but the drawing is not worked out to scale, many details of the general assembly are obscure, and though many individual parts are shown it is only possible to identify certain primary principles of operation which appear in other abortive studies of the loom. It is evident, however, that some of the fundamental problems were understood. It is especially important that the shuttle should not rebound when it reaches its box at the end of its run; with Kay's attachment for the flying shuttle, a possible rebound was checked by a movement of the wrist, but attempts to drive the shuttle mechanically were long frustrated by the difficulty of stopping the shuttle without rebound. Leonardo provided arrangements of springs which would certainly have accomplished that purpose even if other difficulties were created. The shuttle was to be carried half-way into the shed by an arm operating from one side and then picked up by another arm that entered the shed from the other side. Later applications of the same idea appear in the projects for a power loom by de Gennes in 1678 and by Vaucanson in 1745.[203] This idea proved to be a false lead for the broader looms required for fabrics wider than ribbons, but it is perhaps not an exaggeration to say that elements of such a conception appear in the ribbon loom. In this instance, Leonardo pitched upon the same notion that occurred to other early inventors working on the loom, but on the whole it was not a proper basis for the solution of the problem. It was easier to define the problem than to solve it.

Leonardo's proposed shearing engine encountered similar difficulties. There are numerous sketches; some of them based upon the notion that mechanical attachments were to be applied to the hand shears regularly used by the craft of shearmen, others representing attempts to devise a cutting apparatus wholly different in principle. He was able to separate the blades but he could not emancipate himself from the general idea of bringing

[203] Barlow, p. 230, with plate.

two blades together with a reciprocating motion. English inventors were still working on this lead in the years 1792–1815 though American patents of 1792 and 1793 brought out the basic concept of knives set in a spiral on a cylinder working against a bed plate—an arrangement now familiar in the lawn mower which ultimately developed out of the cloth-shearing machine.

The processes of silk doubling and twisting with which Leonardo

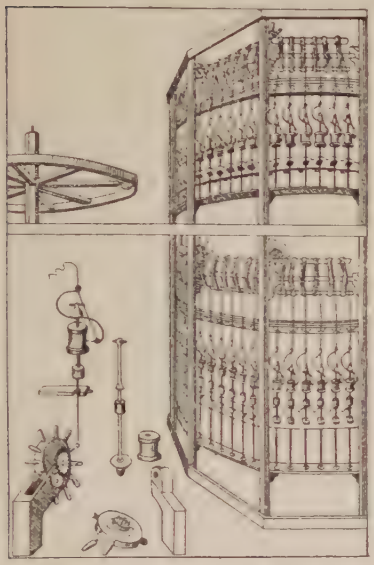


Fig. 84.—The Piedmont silk mill; Zonca: stationary external frame.

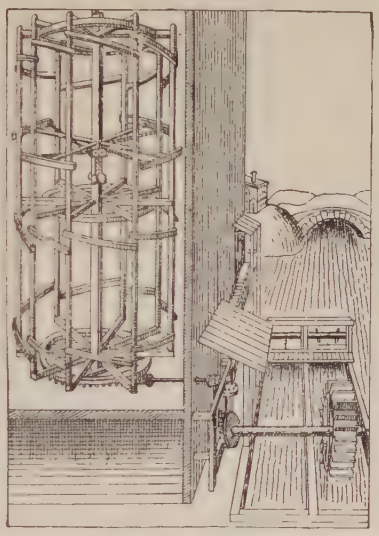


Fig. 85.—Piedmont silk mill; Zonca: internal driving frame.

was clearly occupied, if not already in use, were successfully placed upon a mechanical basis in the period immediately following. In Zonca's treatise we find the earliest complete representation of the machine that came to be known as the Piedmont mill. Figs. 84 and 85.[204] The machine consists of two pieces of framework: an outer frame, shown in Fig. 84, which carries the spindles and the reels; an inner frame Fig. 85 which is arranged to rotate about the central post. The spindles are turned by friction set up between the small cylinders fixed below the spools and the strips of wood set on the inner frame. The reels are turned by the action of the inclined bands of wood upon the arms of the wheels that protrude from each section of the frame.

[204] Beck, G. M. B., p. 304, Figs. 366–367.

The machine is designed to give the final twist to silk thread that has already been formed by the combination of several filaments loosely twisted together. The doubled silk is on the spools and is thus wound from the spindles to the reels above. Pariset identifies this type of mill with the mill invented at Bologna in 1272 by Borghesano,[205] but even if the primary principle may be carried so far back it is difficult to believe that the mills were built on the scale indicated by Zonca in the earlier period. The mill as shown in the figure dominated the industry for generations, and had not passed out of use in Italy even at the close of the nineteenth century. This mill was introduced into France in 1670 and into England in 1718. The early application of machinery to the silk industry probably indicates that mechanical obstacles were a serious factor in the postponement of the mechanical spinning of wool, flax, and cotton. These fibers, especially wool and flax, presented a number of difficult problems. The necessity of drawing out the fibers in the process of spinning presented a serious problem of principle: the physical properties of wool and flax presented puzzling problems of practical detail, which were, in fact, solved only after the general principles had been worked out in the cotton trade. Under the circumstances, no solutions were forthcoming in the earlier period when the first attempts were made to develop machinery in the textile trades, and the actual accomplishment was therefore postponed until economic pressure gave a new stimulus to inventive effort.

IV

The first group of modern textile inventions is brought to a close by the invention of the stocking frame and the ribbon loom. Both inventions were of subsidiary importance from the point of view of economic development, but they are interesting as affording further evidence of the precise limitations of the mechanical competence of the sixteenth century.

The early history of knitting by hand is not known. Various accounts of its antiquity and place of origin are given, but none are substantiated by adequate evidence. Knit goods, if made, occupied an inconspicuous position in consumption until the close of the fifteenth century. Thereafter, the vogue spread rapidly over Europe; caps were made of wool, hose were made of wool or silk. Prior to the introduction of knitting, hose were made of

[205] PARISET, "*Les industries de la soie*," p. 115.

cloth and, for obvious reasons, could not be made sightly or comfortable. The new fashion spread rapidly during the early part of the sixteenth century, and the increase in the demand led to the invention of the knitting frame. We have only the scantiest knowledge of the early state of the invention, in fact, no details of construction that are much nearer than a century to the actual date of the invention. Much uncertainty also attaches to the place of the invention, the personality of the inventor, and the date. The French later claimed that the knitting frame was first invented in France at the beginning of the seventeenth century. Some stories about the invention by William Lee contain incidents so remote from any possible events in the life of the recorded William Lee that the whole story has been discredited in the minds of various writers. The works of Hanson and Felkin, however, have sifted all the accounts and their conclusions have won general acceptance.

William Lee, the curate of Calverton, a little town near Nottingham, occupied himself with the process of knitting and completed an invention about 1589. With the help of his brother James a number of persons were taught to use the machine and several frames were made. After a couple of years, a machine was taken to London, where it came into use among the silk workers of Spitalfields, and later at Godalming in Surrey. Attempts were made to secure from Elizabeth a patent of monopoly, but to the best of our knowledge none was granted. After the queen's death, the attitude of the new sovereign proving discouraging, Lee proceeded to France at the instance of Sully, the minister of Henry IV. The king was assassinated, however, before any arrangements were concluded and the hostility towards Protestants precluded any hopes of success under the new régime. William Lee died in Paris in 1610. French claims to the original invention seem to be based upon this attempt to secure the favor of Henry IV.

The machine was originally designed to be operated by foot power, so that in some respects it is merely one of a large class of treadle-worked machines brought out in the sixteenth century; it was, however, much more nearly automatic than most machines of its day, and by its subsequent history it comes to occupy a notable place in the history of the competition between machinery and hand labor. The concentration of the industry around Nottingham, and improvements made in the eighteenth century by Strutt created one of the first firms significantly devoted to the business of making textile machinery.

In its early form the machine was capable of making the web for seamed hose, including the feet. The earliest machines were adapted only to the coarser woolen yarns, but Lee soon improved the details of construction sufficiently to adapt the machine to the making of fine silk hose. By dropping stitches at appropriate stages in the process, fashioned hose can be produced on the machine, though not without some diminution in the speed of operation. Hand knitters were capable of 100 stitches per minute, at the most: with the frame as developed by Lee himself, 1,000 to 1,500 stitches could be formed per minute. The machine seems complex, but is, in fact, easily mastered even by a child of twelve or thirteen. A great economy of effort was thus secured even

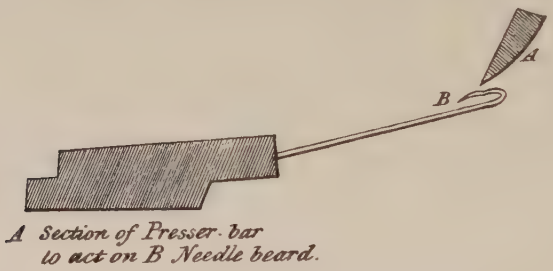


FIG. 86.—The needle of the stocking frame.

when the machine was dependent upon the muscular energy of the operator.

The primary parts of the machine are shown in Figs. 86 to 88.[206] The needle was the first notable innovation. The hook or beard is fashioned to fit into a groove cut in the shaft of the needle, so that the pressure of the bar shown in profile in Fig. 86 closes the opening of the beard and allows a completed stitch to pass over the head of the needle. The elasticity of the needle reopens the beard when the pressure is removed. The stitch is formed in part at the stem of the needle, and in part at the hook. The coordination of these stages in the development of the loop is the work of the second essential operative part, the sinker, shown in Fig. 88. This form is made of metal, at first of tin, later of iron. As they must work in the spaces between the needles, they must be very thin, and sound workmanship must be shown in their execution to prevent injury to the threads and interrupted operation of the machine. The functions of the sinkers are: to press

[206] FELKIN, Plate II, Figs. 1, 2, 3, facing p. 49.

down the thread laid across the needles so as to form the loops at the beards shown in Fig. 87; to draw back to the stem of the needle the completed loop that has just been passed over the closed beard;

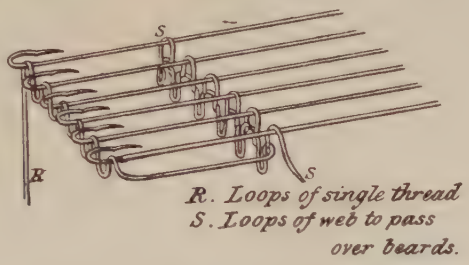


FIG. 87.—Formation of the loop.

to push forward over the depressed beard the incompleted loops at the stem of the needle. The vertical movements of these sinkers are produced by the action of the levers *L* in Fig. 88. The springs *k* maintain the levers in the correct horizontal position

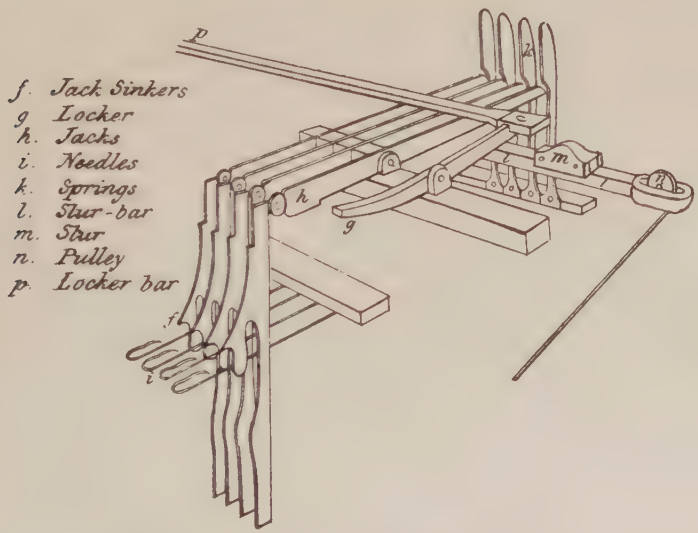


FIG. 88.—The sinker of the stocking frame.

by offsetting the weight of the sinkers. The movement backward and forward is secured by mounting these central parts of the machine on a carriage which can be drawn forward or pushed back by the operative. This arrangement may be seen in Fig. 89, which

shows the general features of the assembly.[207] The carriage moves on wheels, as indicated at *ii*; it is drawn forward or pushed back by the handles *ll* shown at each side of the frame. The presser

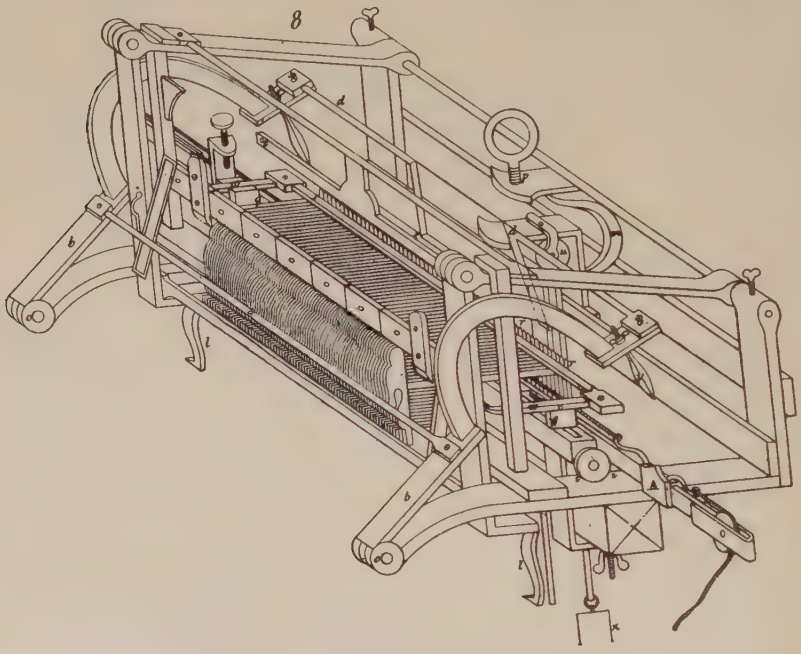


FIG. 89.—An early stocking frame.

bar *a* is carried by the arms *bb* whose further ends are connected by the bent bar *dd*. This bar *dd* is operated by a pedal not shown in the diagram: the presser bar is obviously depressed when the pedal is depressed, and lifted by a counterpoised weight suspended from the pulley *u*. The vertical movements of the sinkers are controlled by the locker bar and locker (*L* and *g* in Fig. 87: *f* and *w* in Fig. 89); and by the slur (*m* in Fig. 88, *A* in Fig. 89). The cord by which the slur is moved is unfortunately omitted in the drawing in Fig. 88. The arrangement is correctly shown in Fig. 89. This cord is operated by pedals. The operative handled the thread only in throwing it over the needles from the bobbin; all the other motions were produced on the machine, though a substantial series of motions by hands and feet were required to complete the operation. The series of motions is rather more complex than is involved in any of the hand looms for the simpler

[207] BORGNIS, "*Mécanique appliquée*," Vol. VII, Plate 35, Fig. 8.

types of goods, and rather more mechanism is involved than in the draw loom in its earlier stages of development. The stocking frame thus stands in an intermediate position between the earlier textile apparatus and the machine in which power was successfully applied at the close of the eighteenth century. It is very closely comparable to the mule, prior to the development of the self-actors in 1825. The operative was not only a source of power, but also a means of coordinating the movements of the various parts of the machine. The stocking frame is, none the less, the basic invention that underlies the whole family of knitting and lace-making machines developed in the eighteenth and nineteenth centuries. The basic inventions of all these operative mechanisms precede by a considerable interval the development of the supplementary parts and devices by which all intervention of the operative was eliminated and the machine was adapted to the application of mechanically produced power. Such applications of power brought to an end a long series of inventive efforts directed towards the more perfect constraint of motion. In the words of Reuleaux's formula, pair- and chain-closure was substituted for force-closure. But all these efforts resulted in nothing more than the completion of a scheme or pattern which is clearly implicit in the simplest application of the basic invention. The nature of resistance to the complete achievement is extremely complex. It is, in part, economic. There may be no incentive because of cheap labor, or positive resistance by craft workers. In part, it is a lack of mechanical competence to execute the project in its ampler form.

The history of the ribbon loom is similar in many respects to that of the knitting frame, but the details of the story are even more obscure, and it is only by careful inference that it is possible to form a sound concept of the machine as it existed prior to the important improvements in the early eighteenth century by John Kay and Vaucanson. There are two accounts of the original invention. According to a Venetian writer of 1629, a loom for weaving several breadths of ribbon simultaneously was invented at Dantzig about 1579. The city council was apprehensive lest many poor weavers be thrown out of work and had the inventor secretly strangled. A Dutch writer says that this type of loom was invented at Leyden about 1621. Whether these achievements were connected or not, we do not know, but it is quite certain that the substantive history of the ribbon loom begins in Holland rather than in Germany. We have the text of ordinances of 1623, 1639,

and 1648 regulating the use of such looms in Holland, and it is thus evident that the looms were known in Holland by the time suggested as the date of the invention. There is no confirmation of the later statement crediting Holland with the actual invention, independent of knowledge of the earlier achievements credited to

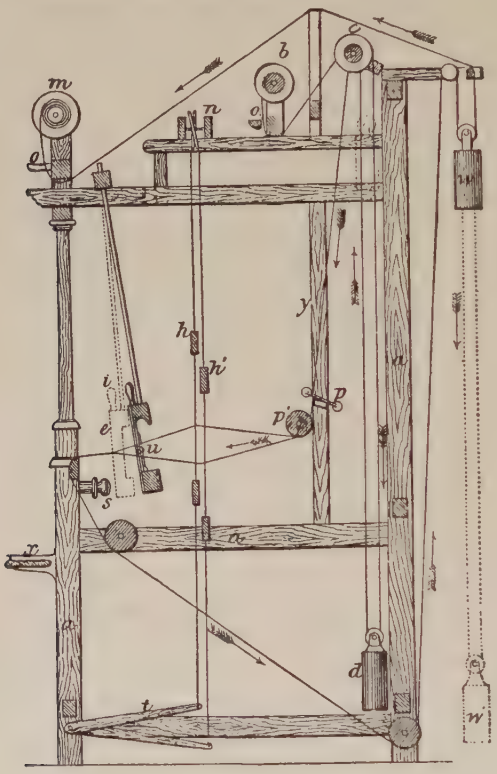


Fig. 90.—An early ribbon loom.

Dantzig. After 1650, further indications of the use of the loom occur in regulatory ordinances in the Spanish Netherlands, Nuremberg, and Cologne. By the close of the seventeenth century the use of the loom was extended to the more important ribbon-making districts of Germany, Switzerland, and England and the loom was known in France though not thoroughly established.

The early state of the ribbon loom is shown in Figs. 90, 91, and 92.[208] The profile of the machine appears in Fig. 90. The primary parts and operations are described by Barlow as follows:

[208] Barlow, p. 224, Fig. 248; p. 227, Figs. 252–253.

"The loom is provided with as many reels or small warp beams as there are pieces of ribbon to be woven, also with a similar number of cloth beams, upon which the ribbons are wound as they are woven. If this were not the case, every piece must be supplied with weft at every throw of the shuttles, and should one of the pieces fail to receive any weft there would be great difficulty in turning back so as to keep all the pieces alike. In weaving plain ribbons the weft may be broken and pieced again at any interval, for the ribbon does not travel unless the weft is supplied. The reed in beating up the weft actually pushes forward the ribbon as it is woven, each beat of the batten pushing the ribbon, according to the thickness of the weft and the tension there is upon the warp and cloth beams.

"In the figure, let *b* represent one of the warp reels from which the warp for one piece of ribbon passes over the pulley *c* and downwards to the weight *d*, which has a pulley under which the warp passes, and then continues its course over a second pulley at *c*, thence under a cylinder or beam at p^1, and through the heddles b^1 and *b* and the reed *u*. After it is woven, it returns under the loom in the direction of the arrows, and under another weight *w*, and is finally wound on the reel *m*.

"Now if both the weights *d* and *w* be equal, it follows that the blow of the reed will beat up the cloth with a force equal to the friction to be overcome, caused by the silk passing under and over the various pulleys and rails; and as the weight *d* rises, the weight *w* falls, carrying with it the ribbon as it is woven. Thus, by altering the relative proportion of the weights, more or less tension can be put upon the cloth, and the ribbon may be woven with more or less compactness in consequence.

"When the weights have arrived at their full extent of motion, they are replaced in their former position by slackening out more warp and winding up the woven ribbon."[209]

The detail of the shuttle is shown in Figs. 91 and 92, both a front view and a section. The reeds for two pieces of ribbon are shown at *RR*, occupying spaces in the reed frame or batten. When the shuttles are at rest, they are held by grooves cut in the reed frame between the reeds. They are in this position when the reed beats up the cloth as shown by the dotted lines *ei* in Fig. 90. When the batten is swung out and the shed is opened, the shuttles are jerked across the opening by a movement of the handle *h*,

[209] BARLOW, p. 225.

(Fig. 92), by which a series of fingers *e* are struck against the series of shuttles. Each shuttle thus occupies alternately the spaces on the side of its reed opening; the shuttle shown in this diagram thus occupies alternately the grooves *s'* and *s*; its nearest neighbor in each case moving into the space temporarily vacated. The motion of the shuttle is stopped by the finger *e*, which in each case prevents a shuttle from running through the groove into the next reed opening. In 1745, John Kay took out a patent covering the con-

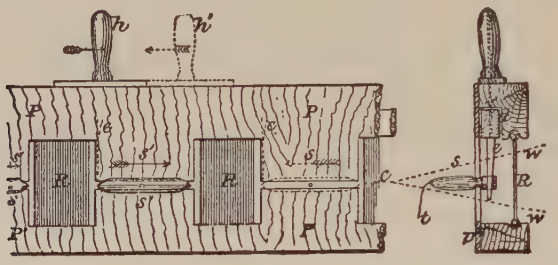


FIG. 91. FIG. 92.

FIG. 91.—Swivel shuttle; front view.
FIG. 92.—Swivel shuttle; section.

trol of the pedals by tappets whose motions were thus directly coordinated with the other motions of the machine. Vaucanson is credited by English writers with the development of the operating bar and the rack-and-wheel motion to govern the spindles. These improvements were certainly made at about this time though the documentary material on Vaucanson's achievements is so incomplete that this work is not mentioned in the primary French accounts of Vaucanson's career. These changes had the net result of making the ribbon loom substantially automatic. The operator merely supplied power and stopped the loom to tie broken threads. Some mechanism for stopping the loom would, however, be essential to the realization of the full economy to be gained from the application of power from general mechanical sources, for as long as the continuous attention of an operative was necessary to stop the loom when the weft threads broke, the operative might as well be required to apply muscular effort to run the machine. Cartwright appreciated these needs of an effective power loom, though he was not successful in achieving practical solutions of his problem and his successors concentrated attention on other features of the mechanism.

The ribbon loom thus embodied all the essential mechanical principles of automatic weaving, at least as early as 1760–1765. In addition to the weft stop motion, however, it left one other problem to be solved; the very difficult problem of control of a shuttle operating through a wide web. In a sense, this was a problem of scale rather than of principle; but throughout the history of mechanism, enlargement of scale frequently creates difficulties that are as serious as if they involved wholly new principles.

V

The development of the supplementary devices needed for the control of the shuttle in the broad loom begins with Kay's invention of the flying shuttle. Whether he had at that time given any serious attention to the ribbon loom, we cannot say, but in a logical sense, his invention really marks a transition from the shuttle motions of the early ribbon loom to the shuttle control of the broad loom. John Kay was a reed maker by profession, and his first contributions to the textile industries consisted in the substitution of wire for split cane in the making of the dents for the reed. A patent was taken out in 1730 for the preparation of twine for some of the incidental work around reeds and looms, and in 1733 a patent for a machine for opening and dressing wool, and for a newly invented shuttle. This must cover jointly the carding engine and the flying shuttle. The arrangements for the flying shuttle are shown in Fig. 93.[210] The reed frame or batten is built out to provide spaces at both ends for the shuttle boxes, and in front of the reed the frame is widened to provide a race for the shuttle. The shuttle is somewhat modified. The curves of the hand shuttle give way to straight lines, the ends are protected by metal points, and wheels [211] are frequently set in the bottom to facilitate its passage over the warp threads that lie on its raceway. Small strips of wood complete the "boxes" at the ends of the batten. The mechanism for throwing the shuttle is shown in detail at *F* and can be readily identified in the general assembly. This "picker" is made of pieces of heavy leather joined by a piece of wood. The weaver sets the shuttle in motion by giving a sharp jerk to the cord attached to the picker. The shuttle is caught and stopped gently without rebound.

[210] HOOPER, "Handloom Weaving," p. 117, Fig. 54.

[211] LORD, J., "Memoir of John Kay," p. 97. With plate.

"The knack of doing this as it should be done, by a simple drop of the hand, is only to be acquired after a great deal of practice."[212]

The fly shuttle increased the speed of weaving, as it freed one hand of the operator and made it possible to devote one hand exclusively to the manipulation of the batten. The pace of weaving was thus sensibly increased. Furthermore, the wider webs could be woven by a single weaver, whereas in the earlier period any cloth in excess of 30 inches in width required two weavers.

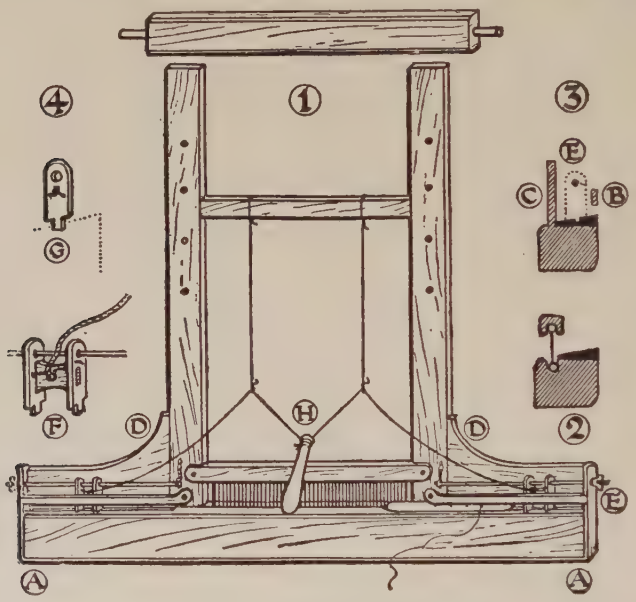


FIG. 93.—The flying shuttle batten.

One at each side of the loom. But the invention also possessed much latent significance, by establishing the general features of a picking motion that might be applied to a power loom. Reference has already been made to the attempts of Leonardo, De Gennes, and Vaucanson making use of arms that carried the shuttle into the web on one side, delivering it to another arm that completed its passage through the web. These suggestions were without significant consequences. In the nineteenth century, some looms were produced in which the shuttle is carried through the shed by a carrier with wheels mounted on an endless belt. The motion of the belt reverses when the carrier reaches the end of the race-

[212] HOOPER, "Handloom Weaving," p. 127.

way.[213] But for the most part a positive drive has found little application outside the field of the swivel loom used for ribbons, tapes, and such narrow wares. Power loom weaving is still based upon the negative drive introduced by Kay. The flying shuttle was thus a strategically important invention, but it created a series of mechanical problems for which practical solutions were found only after an immense amount of critical effort, and technicians even now regard the problem of picking as the most serious defect in the power loom.

"Experience has proved it to be uncertain in action, costly to keep in order, and by far the most dangerous part of the machine . . . When a shuttle is negatively driven, an enormous waste of power results, partly on account of the impossibility of accurately gauging the force required, and partly because the best of motors is liable to variations in speed. A shuttle must never be permitted to rebound after reaching a shuttle box, consequently swells are employed in such a manner that it has been affirmed that the force required to drive a shuttle into or out of a shuttle box is equal to that required for driving it through a shed. On this assumption, three times the actual power required for useful work is taken from the engine, and twice the necessary power must be created by springs or other appliances . . . The movement of a negatively driven shuttle is essentially a jerky one, and frequently produces the most disastrous results."[214]

The warp may be broken, or the shuttle thrown out, and the operative injured. The variations in the speed of the loom, too, affect the operation of the shuttle. At higher speeds, the shuttle is thrown so hard that it rebounds; at lower speeds, it fails to pass through the shed and is trapped. Similarly, variations in the weight of the shuttle affect the operation.

None of these difficulties emerged in serious form until the attempt was made to substitute mechanical controls for the hand of the weaver on the picking stick of the fly shuttle. The barest enumeration of the mechanical elements of the problem will doubtless explain the long interval between the invention of the flying shuttle in 1733 and the development of a practical power loom at the beginning of the nineteenth century. Neither Barber's loom (1774) nor the Cartwright looms (1785–1788) were really practical, and despite the importance of the concepts embodied in the Cart-

[213] Fox, "Mechanism of Weaving," p. 306.
[214] Fox, "Mechanism of Weaving," pp. 266–276.

wright patents, the immediate development of the loom did not proceed from his models. By the close of the eighteenth century, the history of the loom becomes extremely complex; the independent efforts of several inventors were engaged and many of the innovations were not patented and hence were copied extensively without acknowledgment. Furthermore, the changes were refinements in the use and application of known devices rather than new developments of principle. The primary parts of the loom were rearranged so that the machine became more compact and convenient. The cumbersome overhead frame was largely eliminated and the batten instead of swinging from an overhead support was reversed and swung to and fro on pivots at the base of the machine. The cloth beam was moved into a new position. New devices were introduced on the hand looms which reduced the number of the weaver's duties, and with modifications and additions these developments were carried over to the power looms. The primary developments in England were an outgrowth of the work of William Radcliffe with the hand loom (1802). The subsequent development of a power loom was based upon the work of Thomas (William?) Johnson (1803–1805). Horrocks took out patents (1813 and 1821) which were finally developed and improved by Roberts and built by the firm of Sharp and Roberts (1822). Most of the general accounts neglect the work of John Austin of Glasgow. He began work on a power loom in 1789; he made application for a patent, but finally abandoned the notion of patenting his machine. In 1796, the loom with many improvements upon the original plan was studied by members of the Chamber of Commerce at Glasgow and two years later 30 looms were set up at the spinning mill of J. Monteith at Pollockshaws, 4 miles outside Glasgow. Later, another building was erected, containing 200 looms. In 1806, a model with further improvements was sent to the Society of Arts at London and is still in their museum.[215] The machine was provided with both weft- and warp-stop motions. It was capable of 60 shoots or picks per minute, or 2 yards of 900-thread web per hour. One weaver with a boy could tend five looms on coarse work, or three or four on fine work. Even with due allowance for the optimism of the inventor, the accomplishment seems to have been considerable. The general aspect of the loom, reproduced in Fig. 94,[216] seems to indicate

[215] *Transactions* of the Society Instituted at London for the Encouragement of Arts, Manufactures and Commerce, 1806, Vol. 24, pp. 93–97. No plate.

[216] Hooper, *J. R. S. A.*, Vol. 60, p. 996, Fig. 61.

that this invention was not without influence upon the development of the loom in England, which was largely subsequent to its exhibition in London.

Although the development of automatic power weaving is associated almost exclusively with the ribbon loom and the plain loom, important modifications were taking place simultaneously in draw-loom weaving. All the primary accomplishments were embodied in a loom designed to be operated by hand, once the

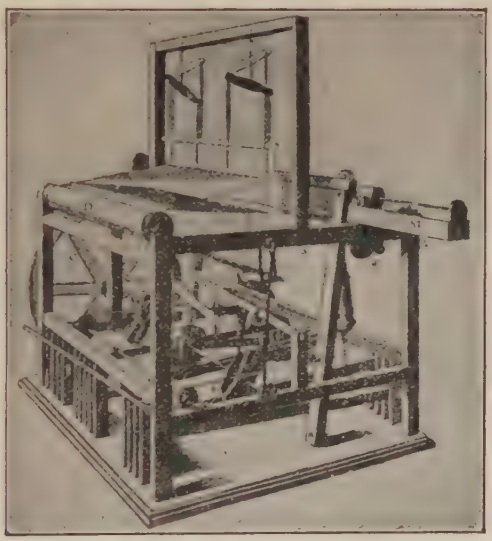


FIG. 94.—John Austin's power loom, 1796–1806.

technique of power weaving was fully established it was a simple matter to apply power to the machine that had been perfected for pattern weaving. The history of this development has long been obscured by writers who were unwilling to recognize the essentially cumulative character of mechanical achievements. The story of the development of the draw loom must be carried back to the introduction of an early form of draw boy by Jean le Calabrais in the fifteenth century. For the narrower fabrics, this device was wholly adequate. The cords of the simple (see Fig. 79*F*) were tied according to the requirements of the pattern to various cords passed through a board. These cords were furnished with handles so that the weaver himself or his assistant could manipulate the leashes of the warp with little effort. This mechanism was further

developed in 1687 in France by Galantier and Blache, and in the same year a patent was taken out in England by Joseph Mason. This system, however, could not be applied to the larger fabrics because the weight of the lingoes on the leashes and the friction on the pulleys required substantial muscular power. To meet the requirements of such a loom the arrangement of the simple with guide cords shown in Fig. 79 was devised about 1609 by a Lyonese workman, Dangon. To assist in drawing the cords of the simple, he also devised an apparatus that enabled the drawer to apply a lever to the task of drawing over and holding the cords of the simple. This arrangement, however, involved a burdensome preliminary task in tying up the cords of the loom with reference to each pattern to be produced: frequently a matter of a couple of weeks. The change of a pattern thus involved heavy costs, for the direct losses in output and labor and for the still more uncertain overhead costs involved in the periods of idleness pending the receipt of orders for a new pattern that had been tied up on the loom in order to produce the samples that were sent around to the trade. At Lyons, in the seventeenth and eighteenth century the task of drawing had fallen to women and at times as many as three were needed at a single loom. The work was heavy, the hours long, and serious physical disorders were developed by this most wretched class of silk workers. Numbers of them were constantly in the hospitals. Increasing competition of Indian silks created much pressure so that economic and humanitarian motives made mechanical improvements desirable.

The first notable achievement was the invention of Basile Bouchon, who perfected in 1725 a device that simplified and lightened considerably the work of the weaver's assistant. The primary features of the scheme are shown in Fig. 95,[217] which is based upon a model prepared in 1851 from descriptions in contemporary documents. The leashes of the loom are represented at *S*, with the appropriate tail cords and simple. The cords of the simple pass through the eyes of a series of needles set in the box *D*. Below the needles each cord of the simple has a knot or bead, and at a slightly higher level than these knots or beads there is a comb bar *G* whose teeth are sufficiently close to prevent the passage of the beads. The teeth of the comb do not reach the cords of the simple when they are in their usual position, but if the needles are pushed back the beads are caught by the teeth in the comb and the series

[217] Barlow, p. 143, Fig. 127.

of cords can then be drawn down by means of a pedal operated by the assistant. The selection of the needles to be pushed back is secured by the sheet of perforated paper which passes over a perforated cylinder. The needles opposite solid portions of the sheet are pushed back by a movement of the cylinder *F* towards the box *D*. The needles thus selected could then be drawn down

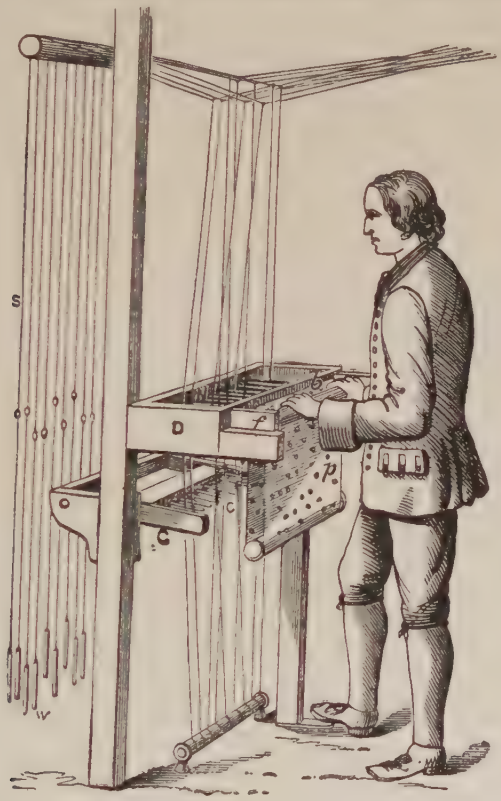


FIG. 95.—Bouchon's attachment for the draw loom.

by the movement of the comb previously described. The attachment was narrowly limited in compass, because provision was made for only one row of needles, and the cylindrical form of the perforated roller did not admit of the addition of other needles. Thus, although Bouchon must be credited with the most original single invention in the series, it was significant for its potentialities, and of very slight practical use.[218]

[218] BALLOT, CHARLES, "*L'introduction du machinisme dans l'industrie française*, p. 339.

The importance of the idea was perceived by a master silk weaver named Falcon, who was successful in securing a small pension from the Crown and promises of financial assistance from the city of Lyons. He joined forces with Bouchon and in 1737 work was begun on the project, which was thus no more than a critical revision of the original concept of Bouchon, though Falcon made little or no public reference to his indebtedness to the earlier invention or to the continued efforts of his associate. Within two years an improved machine was turned out, which is incorrectly described by the enemies of Jacquard despite the careful account given by Goeffon in 1762. There were two fundamental innovations: an increase in the number of needles by providing for several rows; the substitution of a series of narrow cards for the continuous roll of paper. The series of cards was necessary to provide for the added needles, each card represented the selection of needles required for a single shoot of weft. These elements were embodied in the machine as finally developed, and many have assumed that other important details were also contributed by Falcon, notably the "cylinder" or prism by which the card is pressed against the needles. But Falcon's machine was less developed than the enemies of Jacquard represented. The series of cards was placed in a box behind and above the operative. The cards were led from the box over a square beam mounted on bearings so that the series of cards passed over the operative's head and down in front of the machine. The operative was provided with a platen of the shape of the cards, perforated to match all the possible holes in the cards. Each one of the series of cards must be taken by the operative, fitted over the platen and pressed against the set of needles. The device at this stage merely facilitated the work of the operative, making it more accurate, less fatiguing. The primary economic advantage lay in the simplification of the process of changing patterns on the loom. The mechanism for selecting the pattern was carried in the series of cards, and thus a given loom could be prepared for the production of a different pattern by the insertion of a new series of punched cards.

The device was applied to some looms, but not generally; practical difficulties arose involved rather in details of design than in principle. Opposition developed and in 1755 all government support was withdrawn. Some of the manufacturers gave Falcon financial support, a revised model was completed in 1762, and

political changes gave him further official support. In the course of the next few years, about 40 looms were equipped with one or the other of his devices. Competing arrangements were also developed, notably by Phillipe la Salle.

In the meantime, notable modifications were suggested by Vaucanson in 1747 in the course of his work on the mechanisms of the silk industry. He proposed to do away entirely with the attendant charged with drawing cards. The action was thus completely recast. The apparatus was placed at the top of the loom in the place occupied by the pulley box of the ordinary draw loom (see Fig. 79). The tail cords and simple were entirely done away with, the needles being connected directly with the neck cords by wire hooks; the lower ends of the hooks were fastened to the neck cords, the upper portion of the hooks passed through eyes in the needles. The selection of the needles was accomplished by a cylinder pierced with holes to correspond to a given pattern. Mounted on a carriage capable of motion forward and back, the cylinder could be made to engage the needles: the hooks selected would then be lifted by a motion of an iron rod which was engaged in them as in the fully developed Jacquard action.

This invention represents a curiously intermediate stage: the compass of the machine was seriously restricted by the adoption once more of a cylinder instead of a flat surface, this was a positive retrogression; the new arrangements of the needles, however, the design of the wire hooks, and the directness of action on the neck cords was a decisive improvement of the greatest importance. It was not, however, a finished machine and no attempt seems to have been made either to make it wholly practical or to bring it into use. The whole affair is extremely obscure, but it seems likely that the whole enterprise was seriously affected by the hostility of the workers at Lyons so that work on the loom was discontinued after the general concept of the revised machine had been embodied in a model.

This unfinished task was resumed by Jacquard at the instance of certain Lyonese manufacturers. Accounts of his career are confused, but it is certain that he had begun work at least as early as 1800, on an action to manipulate the leashes of the draw loom. Some assistance had been secured from the republican government, and he was working in the Conservatory of Arts and Crafts. At this point he was urged by Dutilleu to hunt up the model of the Vaucanson draw-loom action which was, in

fact, discovered after a long search. It was in need of substantial repairs. After careful study and reconstruction of the model, Jacquard returned to Lyons (1802–1803), where his first loom action was built in 1804. The elements of Vaucanson's general design were combined with the primary operative details of Falcon's action, so that no essential feature was really original with Jacquard and consequently many have attempted to minimize the quality of his achievement. Such hostile criticism is based upon the naïve misconception of the processes of invention and achievement. It is quite true that little remained to be done in respect of the individual parts essential to the action, but the composition of these somewhat isolated elements was in itself no small achievement and the effective execution of the plans was an accomplishment of the highest order. Jacquard was assisted in his final work by several skilled workmen, but that hardly diminishes the distinction of his work. It is certainly inaccurate to say that "few people ever received so much credit for doing so little."[219] It is the rule rather than the exception that the final achievement should be credited with the total accomplishment. Public acclaim shows little delicacy in descrimination, but it is not sound to proceed to the other extreme, giving all the praise to the formulation of the barest concept of principle and refusing to acknowledge the magnitude of the concrete work of composition, development, and critical study of the problems of proportion and design. Each step in the process is equally essential and though they do not encounter absolutely equal resistance, it is none the less true that significant difficulties are not as an end even when the principles are fully worked out. Jacquard and his associates started with the fragments of a highly refined piece of mechanism; they worked with such thoroughness that no primary feature of the action has since been changed.[220]

Sections of the essential part of the action are shown in Figs. 96 and 97.[221] They show a tier of eight hooks with the needles by which they are operated. The complete action usually contains between 100 and 900 needles, according to the size of the loom and the number of individual leashes attached to each neck cord. When many leashes are fastened to a single neck cord the

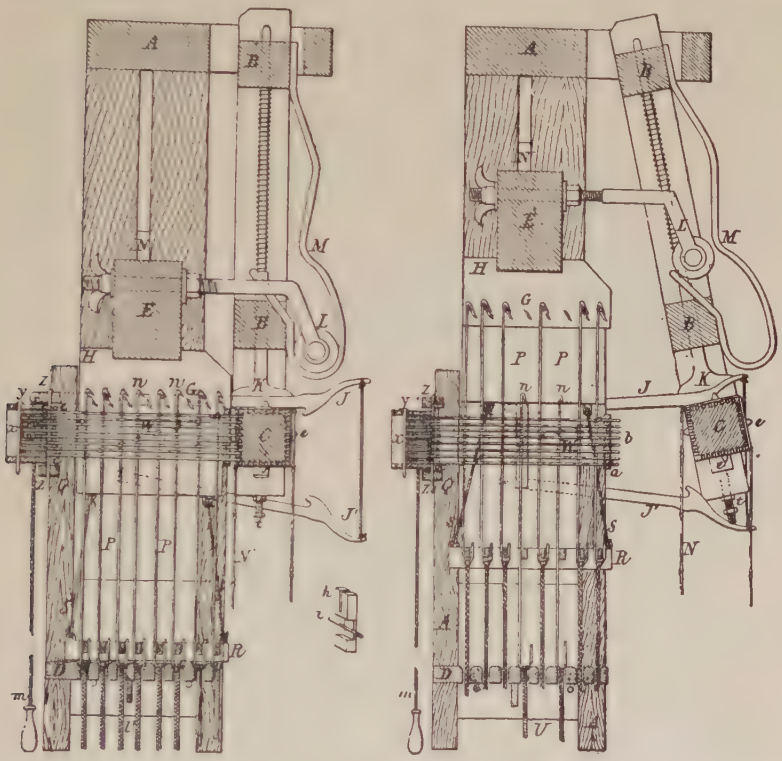
[219] Fox, "Mechanism of Weaving," p. 119.

[220] Ballot, Charles, "*L'introduction du machinisme dans l'industrie française*," pp. 334–382.

[221] Barlow, p. 151, Figs. 130–131.

freedom of work is restricted and the same pattern must be repeated with proportionate frequency in the given width of fabric.

The neck cords of the loom *U* are brought up through the perforations of the board *D* and slipped over the open end of the hooks. When all the hooks are at rest on the board *D* the open



FIGS. 96 and 97.—The Jacquard action.

ends are occupied by bars carried on the frame *R*, so that the hooks are firmly held at the bottom. When in this position the tops of the hooks are free, as the hooks rise slightly above the griffe bars *G* set in the end plates *H*. Each hook passes through the eye of a needle, which is held in place by small spiral springs active between the pins *YZ*. This portion of the action was contributed by Vaucanson. The moveable arm *BB* with its revolving beam or "prism" *C* was new in all its details. Falcon had provided for the operation of the needles by a loose platen

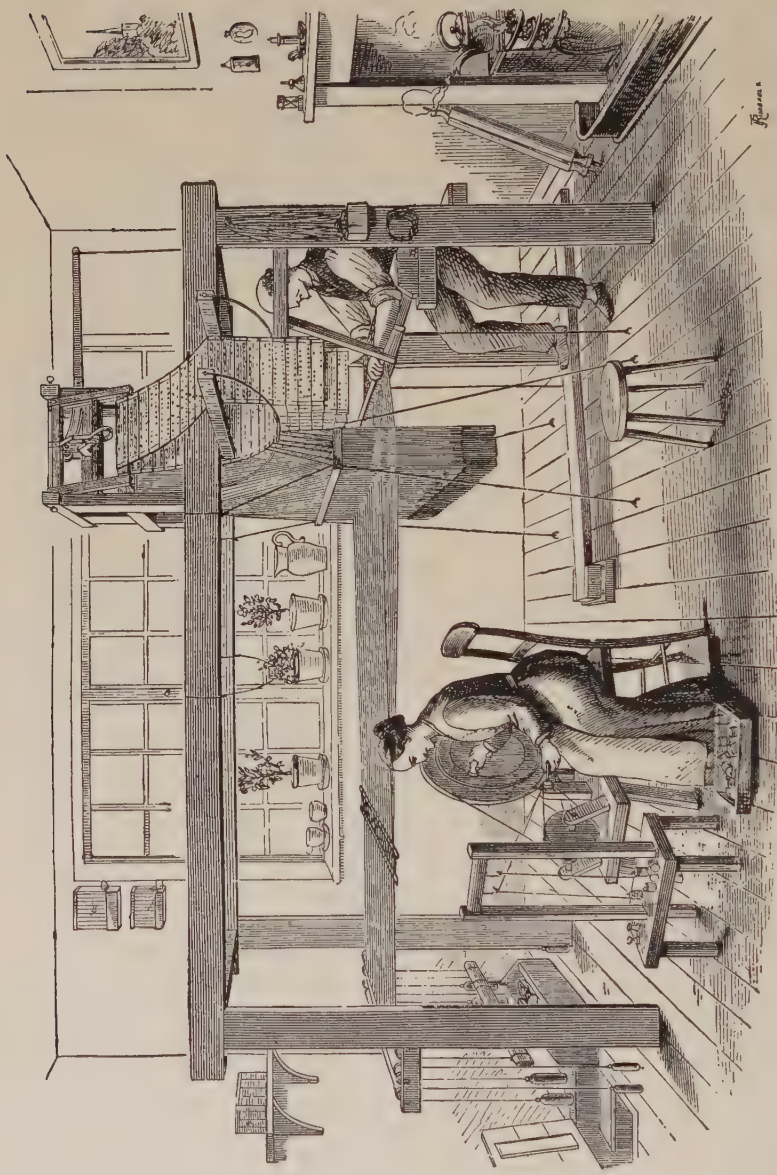


FIG. 98.—Handloom with Jacquard action.

pressed against the cards by an operative. Vaucanson abandoned the cards and used a cylinder on a carriage. Jacquard converted Falcon's feeding prism into an integral part of the machine and developed the arm operated by the swan's neck *M*. The beam or prism *C* is thus new in this form. It is perforated, not with the pattern to be woven, as in the case of Vaucanson's cylinder, but with holes to correspond to all the needles in the action. The selection is secured by the chain of cards *N*, as in Falcon's first machine. The exact registry of the cards passing over the prism is ensured by the bosses indicated at *e*. When the prism bearing a card is brought up against the ends of the needles those which encounter blank spaces on the card will be pushed back, whereas those finding holes in the card will fit into the corresponding holes in the prism. The eyes of the needles that are pushed back will act upon the hooks, pushing them back sufficiently to clear the griffe bars under them. At this stage, other devices lift the plates *H*, the griffe bars engage the hooks that have not been pushed back so that hooks, neck cords, and the leashes of the loom are raised to permit the passage of the shuttle. Each card and each stroke of the prism against the needles represents one shoot of the shuttle: the lifting and return of the griffe must thus be completed between the swings of the arm. The turn of the prism must be absolutely complete before it engages the needles. The practical effectiveness of the machine depended upon the accuracy with which these motions were coordinated.

The general aspect of the draw loom fitted with the Jacquard action is shown in Fig. 98.[222] In the power loom some changes of arrangement were necessary but they involved no serious difficulty.

VI

From the beginning of the sixteenth century to the third decade of the eighteenth century there was no significant invention of the field of spinning. The foot-power wheel came into general use over large areas of Europe for the preparation of woolen, cotton, and linen yarns, but the older methods had not entirely disappeared even then. It is frequently said that the spinning inventions were due to the pressure upon spinners created by the invention of the flying shuttle. If one considers only the dates of the developed throstle, the jenny, and the mule this account might seem highly plausible, but if the history of the

[222] BARLOW, plate facing p. 158.

spinning inventions is carried back to include the work of Wyatt and Paul, the beginning must be thought of as essentially contemporaneous with the introduction of the flying shuttle. The patent for the flying shuttle is of the year 1733, though the date is often incorrectly given as of 1738. Wyatt's son declared that the notion of spinning by rollers was conceived by his father in 1730, and that the first machine was built in 1733. It is not possible to verify these recollections, but considerable work must have been done prior to 1738 when a machine was patented in Lewis Paul's name. The two men must have been closely associated for in 1741 they had a spinning mill in operation at Birmingham supplied with power from a capstan with two asses. Even if the Wyatt claim has been somewhat embellished, one must presume that the concept of the new process of spinning was contemporaneous with the introduction of the flying shuttle. From the beginning of work by Wyatt and Paul, the effort to perfect the application of machinery to all the preparatory processes was essentially continuous. Economic factors undoubtedly played a part in this persistent critical study of the basic invention, but it is certainly a serious error to neglect the notable increase in mechanical proficiency which was exhibited by the emergence of ambitious schemes for the general application of machinery. The dates of decisive practical achievement were conditioned more largely by the mechanical difficulties encountered than by conscious selection of particular processes for successive development. The spinning achievement preceded the large achievements in weaving because the mechanical obstacles were much less considerable.

The spinning inventions involved two wholly new concepts: the application of rollers to the manipulation of yarn; the mounting of spindles upon a moveable carriage in order to reproduce the essential features of the drawing out of the yarn as accomplished in hand spinning. Here, as in all inventions we have to deal with an elaborately graded accomplishment even in the evolution of the full consequences of the basic concepts. Fortunately, the episode is sufficiently documented to admit of no serious doubts of the primary facts, though some details cannot be verified.

Wyatt and Paul must be credited with the wholly new concept of applying rollers to spinning, but they did not succeed in working out the details of the concept. The patent of 1738, curiously enough, describes the series of rollers that characterizes the

machine as finally developed, but after the possibility was appreciated it was abandoned for the inferior system embodied in the patent of 1758 which is better known because the specifications are there accompanied by a drawing that has been frequently reproduced. The primary feature of the system of 1738 is shown in Fig. 82, the date 1735 attributed to Paul being without specific authority. The sliver of carded cotton or wool (or the roving of loosely twisted yarn) is drawn into the machine by the first pair of rollers. The speed of the second pair of rolls being greater than that of the first, the sliver or roving is drawn out during its passage between the rolls. From the rolls the yarn passes to the spindle and flyer, through the eyes 1*a* and 3. It is finally wound on the spool 4. The drawing shows a building motion based upon the relative rates of revolution of flyer and spool, and upon the rise and descent of the spool produced by the motion of the frame indicated at 5. In the machine as originally produced, there was no provision for an automatic development of such a building motion. The flyers were identical with those on the foot-power wheels, lined with series of hooks over which the yarn could be looped by the operative. As in the spinning wheel, the twist was put into the yarn by the revolution of the spindle and its flyer. In Paul's second patent of 1758, only one pair of rolls is shown; drawing out and twisting must be assumed to take place simultaneously as result of the differences between the speed of the rolls and the speed of the spindle and flyer.

It is possible that this change was due to the practical difficulty that develops in throstle spinning. When the drawing is accomplished between the pairs of rolls, the yarn is subjected to its maximum tension before it receives the twist that gives it strength. To meet this difficulty the process of mechanical spinning was explicitly divided into two stages which had been but vaguely represented in hand spinning. The hand spinner had long been accustomed to roll the carded fibers into a loose roving either between the hands or upon the thigh. The preparation of the roving became a definite stage in mechanical spinning. The carded fibers are twisted, but not drawn out. The machine used for this purpose is largely identical with the throstle though the adjustments are different, and rolls are no more than a device for feeding the sliver of carded fibers continuously into the machine. By this means, the fibers can be given some twist before they are drawn out. Wyatt and Paul's abandonment of the drawing by two pairs of

rollers was probably due to these difficulties of practice, but we have no detailed knowledge of the different types of machines built by them, or of the nature of the respective contributions of the two men, least of all of the technical purposes actuating the different experiments. The patents, especially the patent of 1738, are vaguely and generally phrased so that we cannot feel certain of the state of their knowledge of the devices suggested to us by their descriptions. It is evident that they engaged in a wide range of experimentation and that their final choice fell upon a type of machine that was actually less adequate than the type finally perfected under Arkwright's leadership.

It is commonly supposed that Arkwright had direct knowledge of the work of Wyatt and Paul, and Highs (Hayes) testified in 1785 that he had made a model many of whose elements were embodied in Arkwright's machine. In addition to these contacts, he had at his command the services of a clockmaker of Warrington and the financial means and technical knowledge of Strutt, the knitting-machine maker of Nottingham. Arkwright was thus responsible for the direction of a protracted effort of critical revision of an invention whose basic principles had already been clearly conceived. To the general features of the famous water frame he contributed much less that was original than did Jacquard to the loom action that bears his name. But even the scant information available shows clearly that the mechanical details of the spinning machine were notably developed and the process of spinning significantly revised.

The throstle or water frame was capable of spinning only the coarser grades of yarn, which were comparable with most of the sizes that had been used in the early English cotton industry, but wholly unsuited to the weaving of fabrics that could compete with the finer Indian muslins and calicoes for which yarn was being imported at heavy cost from India. The throstle, thus, did not solve all the essential problems of mechanical spinning. Fine spinning by machinery has been based upon a somewhat different principle, designed to draw out the yarn at a later stage in the process. Rolls are used in the machine as finally developed, but they function as feed rollers. They are a mechanical refinement and serve primarily to dispense with certain labor of attendance. The essential feature of the machine is the moveable carriage, by means of which the drawing out is accomplished. As the twist is imparted to the yarn by the rotation of the spindles which com-

mences before the carriage begins to move, the twisting proceeds rapidly before any draught is placed upon the yarn. As the carriage moves back during the process of spinning, more and more drawing out is accomplished. At the end of the run, the spindles run for a moment after the carriage has stopped to put in the final twist. With this type of machine it has been possible to rival and even surpass the most delicate accomplishments of hand spinning.

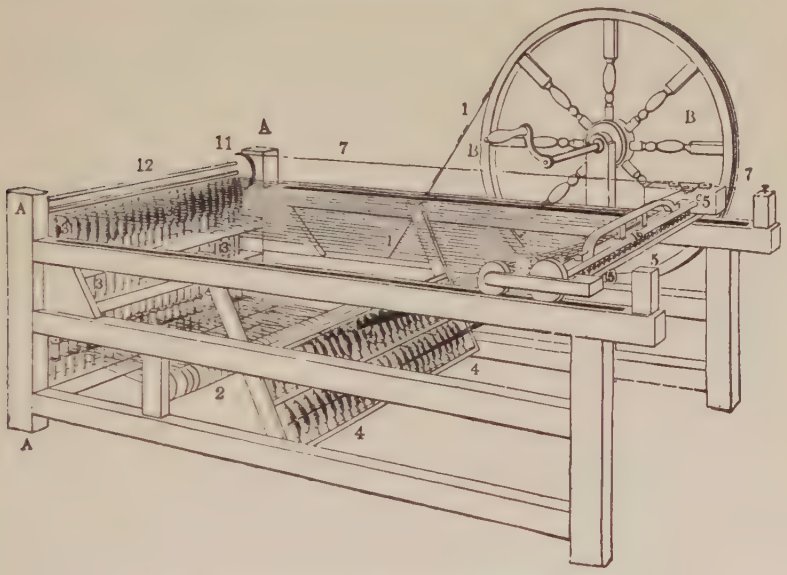


FIG. 99.—Improved form of Hargreaves jenny.

There are several clearly recognizable phases in the development of this principle of spinning. The earliest form was the "jenny" invented by Hargreaves in 1767: essentially an attempt to make it possible for one spinner to control a number of spindles without changing the general motions of either the spindles or the spinner. A somewhat improved model of the jenny is shown in Fig. 99.[223] This machine is a development of the quilling or large wheel in which the spindle carries no flyer. When spinning is in process the yarn is led off the top of the spindle through a notch; by reversing the motion the finished yarn may be reeled. Spinning and reeling thus alternate instead of proceeding continuously as they do in all the machines carrying the flyer. The spindles are turned by

[223] MARSDEN, "Cotton Spinning," p. 205.

power derived from the wheel *B*, transmitted by the driving cord 1-1 to the beam 2 which turns the driving belts or cords for the individual spindles, 3-3. The rovings are wound on bobbins placed in the rack 4-4: they are led up under a bar 16 on the carriage *cc*. The operative turns the wheel with his right hand and manipulates the carriage with his left hand. The plate shows the carriage at the end of its run after the completion of the length of yarn between the spindles and the carriage. The bar has been pressed down on the yarn to hold it firm while the spinning is completed. At the point shown in the figure, the yarn is still running off the tops of the spindles. The spinner must pull the cord 7-7 which acts upon the faller wires 12: by this means the yarn is brought down to the proper level for reeling on the cops. The bar 16 must be released to permit the reeling of the yarn: the motion of the wheel must be reversed and the carriage gradually pushed back towards the spindles as reeling progresses. Reeling continues until all the finished yarn is wound on the cops, in the course of this process a length of rovings has been drawn from the bobbins up over the bar of the carriage so that the interval between the spindles and the carriage is occupied by lengths of rovings. The operative now releases the faller wire; presses down the bar so as to grasp all the rovings; turns the wheel in the direction for spinning; and, after a moment, begins to draw the carriage away from the spindles. At the end of the run, the spindles are turned for a moment to put a final bit of twist into the yarn after the drawing is complete. It will be evident that the carriage with its bar is merely a device for reproducing with several threads the action of the spinner in holding a single thread between the thumb and forefinger.

This invention played a large part in the history of the textile industries for more than a generation. Jennies were built in large numbers and with considerable variations in scale. The machine, however, showed little capacity for mechanical development until important modifications of design were introduced by Samuel Crompton, a jenny spinner of unusual mechanical capacities. Two essential changes were made: the spindles were mounted on the carriage, and the rigid clasp bar was supplanted by one or more pairs of rollers. Because features of both water frame and jenny were combined the Crompton machine was nicknamed the mule. Several early models of Crompton's machine are extant and photographs have been published, but none of these indicate the mechanical principles as well as the simplified sectional draw-

ings reproduced in Fig. 100.[224] This is based upon the modern mule; the number of creels and rollers, and the detail of the faller mechanism differ from the arrangements of the earliest mules. The essential features are unchanged. The rovings are brought from the creels to one or more pairs of rollers and thence to the spindle on the carriage. During the process of spinning, the rollers are stopped so that they hold the rovings firmly. After the spindles have begun to turn, the carriage is backed away from the rolls. At the end of the run the spindles turn for a moment and then the faller wire is thrown over by the arm *K*, the rolls are set in motion and the carriage returns to its starting

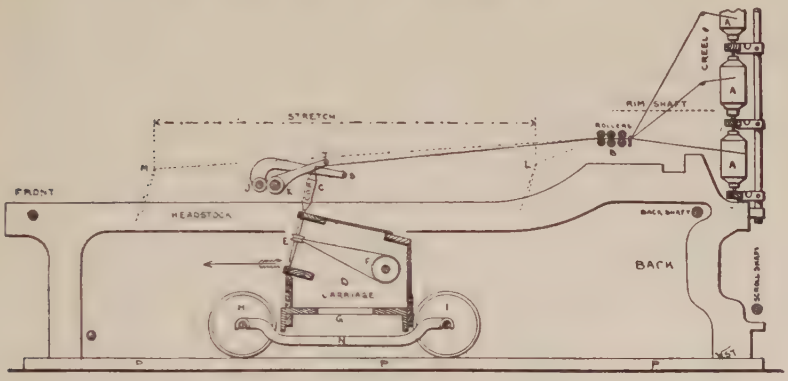


Fig. 100.—Primary features of the mule.

point near the rolls. In the early mules all these motions were performed by hand. The earliest machines carried as few as a dozen spindles, but even the hand mules were considerably increased in compass, and with them England was able to compete effectively with India in the production of fine cottons.

It proved to be a difficult task to devise the parts necessary to make the operation of the mule automatic, and though attempts were made as early as 1790 by J. Strutt, no practical success was achieved with "self actors" until 1825 when Richard Roberts brought out his basic machine. Nine years later, William Smith patented a machine upon somewhat different lines, and most of the subsequent improvements of the mule have been based on one or the other of these machines.

In 1830, a modification was made by John Thorp in the system of continuous spinning which must be ranked as an invention of

[224] Taggart, "Cotton Spinning," Vol. III, p. 26, Fig. 214.

substantial importance. The flyer, so long characteristic of continuous spinning was reduced to the diminutive proportions of a small traveler operating on a ring set in the frame surrounding the bobbin. On the automatic throstle, the bobbin was lifted and lowered by a moving frame inside the fixed flyers. In the ring frame the bobbins are mounted on the spindle: the frame is moved as before, but a flanged ring is fitted to it, and a small traveler working on this ring discharges the functions of the flyer. The primary elements of the operative mechanism are shown in Fig. 101.[225] The yarn passes through a series of rolls, thence to a wire guide *B*, thence to the traveler *C* working on the flanged ring *F*. The frame *G* rises and falls in the process of winding the bobbin. This invention was finally developed into an effective machine in 1833 by Mason and underwent signal improvements between 1867 and 1871. Since that time it has supplanted most of the throstles and competed severely with mules, though it is still impossible to spin the fine, soft yarns on ring frames and the mule persists in a restricted field despite the lower output and higher costs of operation.

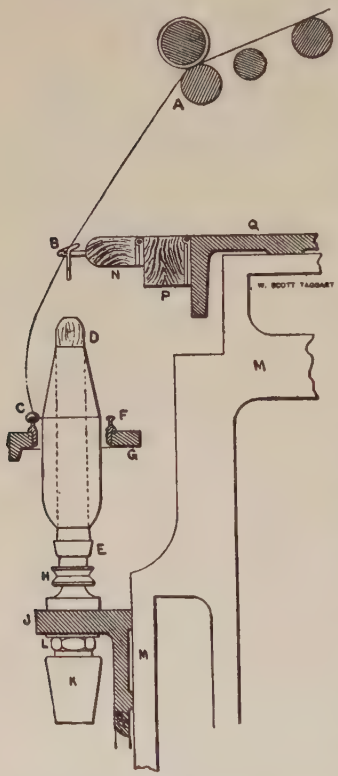


FIG. 101.—The ring spinning frame.

The preparatory and finishing processes required special machinery some of which involved serious mechanical difficulties. Carding engines were developed for the preparation of cotton at an early date by Paul and Arkwright; their work covering, in fact, the whole process from the raw cotton to the yarn though little mention is commonly made of the carding machines, important though they were to the development of factory methods. Wool combing presented a task of greater difficulty and though some success had been achieved by the beginning of the nineteenth

[225] TAGGART, Cotton Spinning, Vol. III, p. 286, Fig. 355.

century the decisive accomplishments were much later. Reference has already been made to the invention of the rotary shearing engine in 1793, with its spiral knives working against a bed plate. The American invention was taken up in England and its use rapidly extended. Its introduction caused more labor troubles than most of the modern textile inventions. The history of these inventions, however, is highly technical and largely a part of the general mechanical development set in motion by the basic inventions. They are an extension of the process of critical revision and exhibit the pressure to mechanize related processes sufficiently to keep the various stages in production in step with each other.

Chapter X

THE DEVELOPMENT OF CLOCKS AND WATCHES INTO INSTRUMENTS OF PRECISION: 1500–1800

I

The history of clocks prior to the sixteenth century is largely a record of essentially empirical achievements. The basic invention, the verge escapement with the foliot balance, was not the work of any single person, and such record as we possess indicates that its development as a significant mechanism of control was accomplished in the course of building practically operative clocks. The beginning of the sixteenth century is marked by the application of springs to the driving mechanism of time pieces, and from this point we pass rapidly into a phase of development that is essentially imaginative and modern. The potentialities of the spring-driven timepiece were immediately perceived, and the attempt was made immediately to realize the full measure of these remote ends. We find conscious application of known scientific principles, scientific research leading to the formulation of new principles, and brilliant imaginative achievement. Although we have to do with the production and control of motion rather than power the influence of newly discovered principles and of the refinement of mechanical concepts was by no means confined to this single field. During the three centuries between 1500 and 1800, the history of clock- and watchmaking is an important chapter in the history of the mechanical sciences, pure and applied. In addition to the direct influences we must recognize the significant part played by these crafts in the diffusion of the knowledge of much applied mechanics.

The use of the weight-driven clock was limited by the necessity of keeping the clock in a single position. The principle had been applied to the making of domestic clocks and wall clocks were constructed in considerable numbers. The use of mechanical timepieces was greatly extended by the application of the steel spring to the driving mechanism of a timepiece whose other parts

were taken over from the weight-driven clock. The foliot balance and the verge escapement were used with only trifling changes in form and arrangement. The initial invention is ascribed to Peter Henlein, a clock maker of Nuremberg, on the authority of a statement by Johannes Dobreck [known commonly by his Latin name Cochleus (Cochlæus)] quoted by Pomponius Mela in his "Cosmographia" (1511). The invention is supposed to have been made during the last decade of the fifteenth century. Other claimants for the invention are frequently noted but no details are forthcoming and none of the primary treatises recognize the validity of the claims of any of these aspirants.

The use of a spring as the driving mechanism created a new problem of regulation, because the spring exerted a variable force, grading from a maximum intensity when fully wound to a minimum when the tension of winding was completely exhausted. In early portable timepieces this difficulty was met by the device known as the "stack freed," a means of exerting a compensating pressure on the driving mechanism. As this device appears on all the early clock-watches that have survived, it was presumably a part of the initial achievement and should thus be credited to Henlein.

The general character of these early timepieces falls between the types which we now describe as watches and table clocks. They were portable, but inconveniently large to be carried on the person. They commonly measured 3 inches or more in diameter; and being relatively thick they were more than one-third larger than the largest, modern-sized, gentleman's watch. At times they were spherical like the clock-watch shown in Fig. 102.[226] The movement was made of iron and steel. The case was highly decorated and during the entire sixteenth century the dial and hands were commonly protected by a metal cover cut away sufficiently to permit reading the dial. Glass crystals did not come into use until after 1610.

The stackfreed may be seen in the view of the movement at the lower right of the plate, and more clearly in Fig. 103.[227] It is a curved strip of metal with a roller on its free end. The roller bears upon an irregular-shaped cam; at the time of winding it lies in a deep hollow out of which it must be forced by the pressure of the main spring, as it approaches a condition of relaxed

[226] BRITTEN, "Old Clocks and Watches," p. 134.

[227] BREARLEY, H. C., "Time Telling through the Ages," p. 100.

tension the relations are reversed and the stackfreed spring contributes a little extra power to the revolution of the driving barrel. In Fig. 103 the main spring barrel turns from right to left, and the figure thus shows the movement in the position

Fig. 102.—Spherical clock-watch, 1535.

assumed soon after it has been wound. This mechanism of control was imperfect and wasteful of power, but it served through the first generation or more of the existence of the clock-watch. A decisive improvement was made by a Swiss mechanic, Jacob Zech, then living at Prague. The dates are variously given, ranging from 1525 to 1540. The unequal power of the main spring was

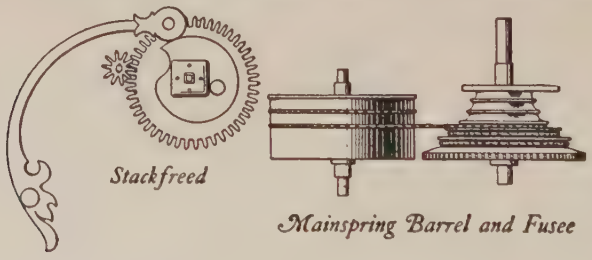


Fig. 103.—Stackfreed and fusee.

compensated by applying it to a driving barrel of varying diameter known as a fusee. The device is shown in Fig. 103. When the spring has just been wound and pulls with maximum power it acts upon the driving barrel on the smallest diameter with correspondingly small leverage. As the power of the spring diminishes the leverage upon the driving barrel increases, so that

the force effectively exerted by the spring is constant if the fusee is correctly designed. This device was ultimately supplanted by other devices in pocket watches, in order to secure a more compact movement, but it is still retained in chronometers, where space is of less moment than accuracy of performance. At the outset the fusee was driven by a cord of catgut, but early in the seventeenth century a metal chain of special construction was substituted, and it is in that form that these parts of the watch movement were stabilized.

The actual measure of time in these movements was the vibration of a foliot balance attached to a verge escapement, shown in Fig. 104.[228] The only actual change in this detail of the clock movement is the mode of attaching the weights to the arms of the balance. In order to make some change of position possible, the weights were pierced through the center and screwed on the arms. Regulation was achieved by altering the position of the weights. The vibration of the balance was supposed to take place in a horizontal plane, so that no force was necessary to raise the weights. Any change in the position of the movement from normal necessarily affected the running of the clock-watch, so that in modern terminology we may say that there was no compensation for the changes of position which we now assume in any watch or chronometer movement.

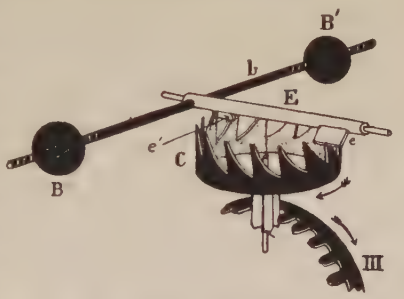


FIG. 104.—Balance and escapement of the early clock-watch.

It is, thus, practically certain that these early clock-watches were less accurate than weight-driven clocks of the period. The movement was likely to contain more elements of error due to imperfections in workmanship. The balance and escapement was distinctly less adequate, if the time pieces were subjected to the changes in position that were inevitable if they were really carried about at all. The inequalities in the force of the main spring would be a serious factor in all stackfreed movements and in any fusee movements that were not designed with great accuracy. Many writers presume that these clock-watches were so inaccurate

[228] GOULD, p. 22, Fig. 2.

as to have no significant value as timepieces, and in their minds these instruments were mere mechanical toys that added to the means of ostentation of the wealthy by the magnificence of their exteriors and their costliness.

There are grounds for presuming that this is an extreme view. Gould believes that the errors of the sixteenth-century movements would not exceed 15 minutes a day. Unless, like Milham, one accepts the present errors of the Dover Castle clock as representative, this error would be vastly in excess of any reasonable daily error of a weight-driven clock, but it would not be so great as to exceed the likely errors of other means of telling time. Neither the water clocks nor the sun dials were accurate within closer margins than the 15 minutes presumed for the clock-watch. The water clocks were certainly a much less adequate measure of time than has been presumed by many writers. Small amounts of dirt in the water, corrosion in the pipes or outlets, or any inaccuracies in the marking of the dial or indicator would affect seriously the accuracy of the instrument. Such devices continued in use because they were cheap and thus accessible to portions of the community that could not afford a mechanical movement of any kind.

The sundial though accurate within narrow limits for the determination of noon, if properly constructed, presented large opportunities for error in design and construction. As yet we are rather imperfectly informed with reference to the standards of construction of dials in the sixteenth century. Modern writers, such as Green and Loschner do not presume a high degree of accuracy for the average dial in the determination of the hours and fractions. Gould says that it would be very difficult to read an ordinary dial within 15 minutes of the time in the intervals between the hours. The dial, too, presents difficulties because of the variations in the length of the solar day in the course of the year. The dial registers apparent or true solar time unless elaborate devices are provided for the indication of the mean solar time that has displaced apparent solar time since the perfection of the mechanical clock. These variations between apparent and mean solar time, called the equation of time, are readily ascertained and may be tabulated for any particular place. In the late eighteenth century, Granjean de Fouchy reduced the equation of time to a curved line appropriate for use on sun dials, and if this be used for the noon hour line mean solar time can be ascertained on the dial for the noon hour. The

same design might be applied to the other lines of the dial, but ordinarily this sophistication is applied only to the noon hour and the curve is frequently called the meridian of mean time.[229] The maximum difference between apparent and mean solar time is about 16 minutes, so that the confusion between the two versions of time would itself be a not inconsiderable element of uncertainty.

It is likewise possible to construct clocks that will indicate apparent solar time. The first recorded movements of this type are reported at the close of the seventeenth century. There was one in the possession of Charles II of Spain, and Sully, the French clock maker, says that they had been made commonly in London.[230] Timepieces of this type were by no means uncommon in the eighteenth century. We may therefore presume that sundials and mechanical timepieces supplemented each other for the better part of two or three centuries and that no decisive attempt was made to give exclusive validity to either version of solar time. For scientific purposes the slightly different sidereal units were largely used. In view of the deep-seated confusion betwen the concepts of apparent and mean solar time, no minute standards of accuracy were essential for ordinary domestic convenience. Apparently, the balance of importance shifted gradually from the sundials to mechanical timekeepers and in this connection we must note the pocket sundials that came into wide use as early as the fourteenth century and remained in use until long after the pocket watch had developed a significant measure of precision. With all their defects, even the early clock-watches were more than mechanical toys. They were not better than average sundials, but they were certainly no worse, and the limitations of the two devices were so different that each possessed distinctive elements of merit and convenience.

The clock-watch of the early sixteenth century developed into two distinct types within a generation of its invention. The makers designed smaller movements that could be readily carried in the purse or used as a pendant. These came to be known as Nuremberg eggs, because they were originally oval in form. Such timepieces were elaborately decorated and were seldom carried in the pocket until the seventeenth century. For domestic use, the movement was enlarged and became a table or mantel clock, provided not infrequently with supplementary features for striking

[229] BIGOURDAN, "*Gnomonique*," p. 113, note 1.
[230] BERTHOUD, Vol. I, p. 184.

the hours and registering astronomical data. There were no changes in general mechanical principle for more than a century following the invention and application of the fusee. Important new inventions appear in the second half of the seventeenth century, but for the moment the development of the watch movement was overshadowed by the transformations of the weight-driven clock stimulated by the formulation of the laws of the pendulum.

II

It is alleged that the Arabs in Spain used the pendulum as early as the beginning of the eleventh century, but the English scholar responsible for the statement cited neither the source of his allegation nor any details.[231] The history of the pendulum begins with Leonardo da Vinci and the Italian engineers of the sixteenth century.[232] They looked upon it as a convenient means of producing a reciprocating motion for use in pumps. Beginning with the seventeenth century, there are alleged applications of the pendulum to clocks. Jost Burgi of Prague is said to have produced in 1612 the pendulum clock now in the Vienna treasury. He was an astronomer and clock maker of substantial talent and there are literary references to work with the pendulum,[233] but the evidence is not conclusive. There was so much making over of clocks at the close of the century that the clock as now preserved is not adequate evidence of its original condition.[234] An inscription in St. Paul's church, Covent Garden, set up in 1800, declares that a pendulum clock was set up in 1641 in a building that had been destroyed by fire. While neither of these claims is impossible, the significant work on the pendulum was done by Galileo and Huygens. The initial work on the theory of the pendulum was done by Galileo, and the studies begun by him in 1583 were embodied in his treatise. In 1641, after he became blind, his son Vincenzio built a clock with a pendulum in accordance with his ideas. Galileo died in 1649, probably before the completion of the experiments, for, though the larger features of the concept were worked out the scheme was defective in many respects and the work had no direct consequence. Both the scientific problem of theory and the con-

[231] Young, Thomas, "Natural Philosophy," Vol. I, p. 191.
[232] Beck, G. M. B., pp. 191, 192, 335, 336, 451.
[233] Becker, J. J., "*De nova temporis demetiendi*," 1680.
[234] Milham, p. 142; Berthoud, Vol. I, pp. 96–97.

cept of a practical application to the clock were taken over by Huygens and carried so far towards solution that only a few matters of detail remained for others to add. Huygens produced his first clock in 1657 and at the same time published a short description of it in Dutch, followed quickly by a Latin translation. The novelty of the invention was at once disputed by Vincenzio Galileo and Huygens published a second treatise in 1658. His final work "*Horologium oscillatorium*" appeared in 1673. Huygens maintained that his clock differed in essential features from the machine of Galileo and that the theory of Galileo was incomplete.

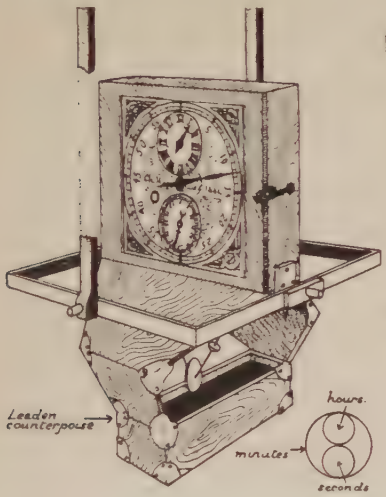


FIG. 105.—Huygen's marine clock.

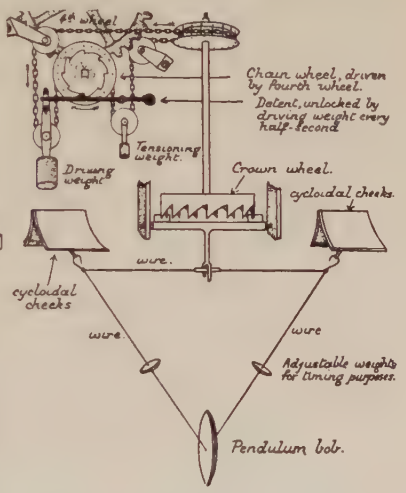


FIG. 106.—Huygen's marine clock.

The primary scientific discovery of Huygens was that the beat of a pendulum was really isochronous only when the pendulum was swinging in a cycloidal arc.

The marine clock built about 1661 is shown in Figs. 105 and 106.[235] The machine was driven by a coiled spring, and had a verge escapement, but this latter was controlled by a pendulum and not a balance. In his pendulum clock, Huygens had, in effect, taken the ordinary verge escapement with balance, as fitted in the "Nuremberg egg," amputated one arm of the balance and lengthened the other. Then finding that the weight of the pendulum ought to move not in a circular arc, but in a cycloid, he had improved upon this by suspending his pendulum by a double, thin cord

[235] GOULD, p. 27, Figs. 5 and 6.

which, as the pendulum swung, was bent around one of two curved wooden cheeks, thus altering the effective length of the pendulum and causing the weight to take a correct cycloidal path. In his marine timekeeper he fitted the same device, but here the pendulum was very short and shaped like a V with the weight at the point. Its effective length was 9¾ inches, and, accordingly, it beat half seconds. The crown wheel, it will be noticed, was set horizontally.

"I have said that the motive power was a coiled spring, but that is only partially correct. There appears in this machine the first published instance (the device is said by some to date from 1600) of a contrivance which has been the *ignis fatuus* of many generations of clockmakers, and whose name, the 'remontoire' includes some of the most ingenious, elaborate, beautiful, and useless contrivances ever made by man. Let Huygens describe his in his own words: 'To the wheel, which has serrated teeth, and is nearest the pendulum, a small weight is hung by a thin and flexible chain. It is moved by this weight alone, and all the rest of the machine has nothing to do but to restore this small leaden weight to its original height every half second.'"[236]

Huygens' work on the pendulum carried the task through the strategic stages of the scientific statement of principles and the first practical application; but the achievement consisted, in reality, of setting a new group of problems, which were not solved in a wholly satisfactory manner until the early years of the succeeding century. The use of the pendulum gave new importance to the length of the arc of vibration characteristic of the verge escapement. This device gave the balance an arc of as much as 20 to 24 degrees, and, unfortunately, these arcs were not uniform over short periods of time though the average was fairly close. None of the old timekeepers could, therefore, achieve any high degree of accuracy. The addition of the pendulum made matters worse. The early pendulums weighed as much as 3 pounds, and considerable power was necessary to maintain the motion of such weight through the long arcs, characteristic of the verge escapement. The machine designed for such a task developed much friction in the pivots of the wheel work and in the escapement itself. There were thus many practical difficulties of detail, which were finally overcome by means suggested by Huygens himself. In his study of the motion of the pendulum, he pointed out that

[236] Gould, pp. 27–28.

very small circular arcs differ insensibly from a cycloid. Thus, the cycloidal cheeks and the long arc could both be eliminated if it were possible to devise an escapement that would operate effectively in a short arc of vibration. It is characteristic of the process of achievement, that this required a new invention: the anchor escapement. This device and an improvement known as the dead-beat escapement are shown in Fig. 107.[237] The crown wheel that is paired with the verge escapement is supplanted by a wheel whose teeth lie in the plane of rotation, so that the entire device is new in every detail of design and operation. Inasmuch as this form of escapement has persisted to the present day, despite experimentation with a large number of other types and forms, the invention of this escapement must be regarded as an accomplishment of the first order. The invention is disputed between Robert Hooke and Clement, though opinion inclines towards the latter and the date 1680 is given by Berthoud.[238]

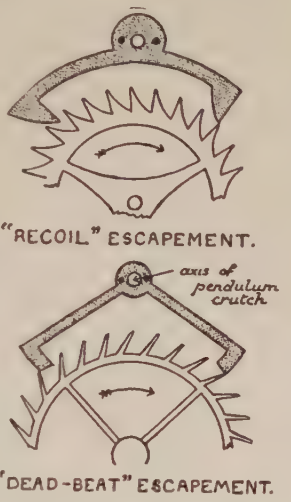


FIG. 107.—The anchor and dead beat escapements.

This invention transformed the pendulum, which came to be a weighted rod suspended by a thin spring instead of a weight suspended by a cord. These changes in turn created new problems in respect of mechanical execution and temperature compensation. The pendulums of the larger clocks became so heavy that the ordinary clock maker was no longer equipped to do the work, and these parts of the task came to be delegated to locksmiths or persons with training in that craft.

The anchor escapement was notably refined by Graham, about 1715. In its original form it was still a "recoil" escapement like the verge. When the teeth of the escape wheel fell upon the inclined surfaces of the pallets, the wheel was first driven backward. There was thus some interference between the mechanism of the balance and its escapement and the driving mechanism. Graham was able to eliminate these undesirable effects by changes in the form of the pallets of the escapement and modification of the

[237] GOULD, p. 150, Fig. 47.
[238] BERTHOUD, Vol. I, pp. 204–205.

design of the teeth in the escape wheel. This is called the "dead beat" escapement because there is no recoil. The pallets of the escapement "drop upon a surface concentric with the arm carrying the pallets, and there is accordingly no recoil." The problem of temperature compensation was not solved until the close of the first quarter of the eighteenth century, when a variety of solutions were proposed by Graham and Harrison in England and by Julian Le Roy in France.[239]

The perfection of the devices incidental to the use of the pendulum established the present distinction between watch and clock movements. The pendulum was applied to all the form of weight-driven clocks; the tower clocks, the cathedral clocks, and the lantern or bird-cage clocks used in private apartments: it was likewise applied to the spring-driven portable clocks that had developed from the Nuremberg egg. The distinction between timekeepers hereafter turned upon the character of the regulating device instead of the source of power. Watch movements are balance regulated: clock movements are pendulum regulated.

During the second quarter of the eighteenth century the clock movement assumed its permanent form. Standards of execution were developed to such a degree, also, that the clock became a veritable instrument of precision. Recent analysis of the astronomical work done with Bradley's clock of 1758 has made it possible to compute the rates of deviation in modern form. It has proved to be more important to achieve constancy of running than absolute accuracy, so that modern tests are intended to express the deviation from the average gain or loss over a period of time, rather than the gross error over a period of some months. Some indicative records are tabulated below.

DEVIATION OF GAINS AND LOSSES PER DAY[240]
FROM THE AVERAGE GAIN OR LOSS PER MONTH

Clock	Date of record	Deviation: seconds per day
Bradley's clock	1758	0.102
Greenwich observatory	1850	0.149
Greenwich observatory	1900	0.051
Berlin observatory	1877	0.02 to 0.03
Leyden observatory	1900	0.028
U. S. Naval observatory	1904	0.015

[239] BERTHOUD, Vol. I, pp. 205–207.

[240] EICHELBERGER, W. S., *Science*, Vol. 25, pp. 450–451.

The eighteenth-century instrument thus performed better than the clock of 1850, but distinctly less well than any of the clocks of the late nineteenth century. In all probability the achievements of Bradley's clock of 1758 were essentially new: they would have been wholly unattainable as late as 1700, and not wholly possible for some time after the important work of Graham in 1715. John Harrison completed two pendulum clocks in 1726, designed to be instruments of precision, one of which did not vary a second a month during a period of 14 years.[241] Though there is no complete record of its mean deviation as computed above, one may presume that the essential problems of the clock had been solved, subject to much improvement in detail.

III

The watch movement was also undergoing notable improvements during this notable period in the history of the mechanical sciences. The strategic invention in this case was the balance spring, which was destined to become a regulating device fully

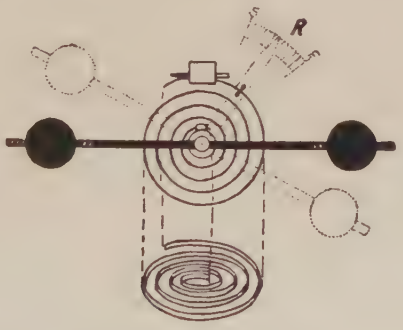


FIG. 108.—Early form of the balance spring.

comparable to the pendulum. In a perfect spring operating under uniform conditions, the force would be directly proportional to the tension. The main features of the device in its early form are shown in Fig. 108.[242] A delicate spring is applied to the balance and escapement of the "Nuremberg egg" movement.

"If the balance, considered for the moment as being at rest and entirely detached from the escapement, be displaced by some external force into the position shown by the dotted lines, the

[241] GOULD, p. 42.

[242] GOULD, p. 22, Fig. 4.

spring will be tensioned, and will set the balance, when released, in motion towards its original position, termed the 'dead point.' The momentum of the weights will carry it past the dead point to a corresponding position on the opposite side of it, and the spring will now be in compression. The balance will then return under the influence of the spring, again swing across the dead point, and continue to go on vibrating in this manner—the arcs which it describes slowly diminishing in extent owing to friction."[243]

Gould declares that this invention "is the most important single improvement ever applied to portable time keepers." It placed the portable spring-driven movement on a parity with the weight-driven movement and held out hopes of the achievement of complete precision of operation.

The invention of the balance spring has been claimed by Huygens, Hautefeuille, and Hooke. But though Hooke's work may not have been known on the continent, owing to the secrecy with which he invested his experiments, there is little doubt of the priority of his work. Huygens was prevented from obtaining a French patent by evidence of prior use presented by Hautefeuille, though it is not intimated that Huygens was actually indebted to anyone for his ideas.

On Hooke's part, at least, the invention was the result of a deliberate purpose to make the spring-driven movement sufficiently accurate to serve as a means of determining longitude at sea. This possibility had been perceived soon after the development of the spring-driven movement. Santa Cruz suggested the use of this method in his treatise of 1520 on the determination of longitude, and in 1530 Gemma Frisius proposed the use of the watch to determine longitude. The early clock-watch, however, was too inaccurate to serve such a purpose and for more than a century the efforts of scientists were concentrated on the discovery of some astronomical means of finding longitude at frequent intervals under the conditions prevailing on board ship. Early determinations of longitude were based upon the observation of eclipses of the sun or moon, but opportunities for such observations are of infrequent occurrence and though suitable for determination of the longitude of places such methods are of limited use at sea. Galileo, in 1610, proposed to use eclipses of the satellites of Jupiter which are of frequent occurrence, but the observation is relatively difficult and no significant degree of accuracy could be secured

[243] GOULD, p. 25.

from so instable a surface as the deck of a ship. Attempts to meet this difficulty were persistent throughout the eighteenth century, taking the form of devices for the construction of a seat or platform that was free from the disturbances due to the motion of the ship.

For marine longitudes, attention was concentrated upon observations of the position of the moon: lunar distances, computed from the sun or from a fixed star were used early in the sixteenth century; the moon's transit of the meridian was proposed as a basic observation in the following century; the use of the meridian altitude of the moon was proposed in the eighteenth century, but was not adopted in practice. Of these methods, the second was theoretically the best, and on land considerable accuracy was possible, but a well-equipped observatory was necessary, and at sea the results were utterly unreliable.[244] The method of lunar distances was long the chief hope of the solution of the problem of longitudes, but there were difficulties of observation and of computation. An error of 1 second of a degree in observation worked out to an error of 30 seconds in longitude and even in the late eighteenth century accuracy within 1 degree of longitude was the best that could be hoped for. In practical use, elaborate astronomical tables were necessary and none were available until the second half of the eighteenth century. As late as 1680, Flamsteed of the Greenwich observatory admitted the likelihood of errors of 7½ degrees of longitude in determinations by this method.

In fact, there was no means of determining longitude at sea sufficiently accurate to serve as a basis for practical navigation. Mariners were obliged to rely upon dead reckoning, and as there were obvious chances of error, wide margins were assumed and the courses of vessels were directed more largely in terms of latitude. It was commonly necessary to plan to reach the latitude of the desired port at sufficient distance east or west to offset any possible error in dead reckoning: on reaching the proper latitude the course of the vessel could then be laid east or west. The technique of navigation thus could not advance significantly beyond the attainments of the late fifteenth century, for want of adequate means of determining longitudes. In the meantime, however, the marine chart had been made an accurate and scientific projection by Mercator (1569), so that the desirability of using the geographical coordinates came to be keenly felt. The increased emphasis upon oceanic voyages made sound navigation much more impor-

[244] MACKAY, "Treatise on Longitude," Vol. I, pp. 217–218.

tant, and the deficiencies of the sixteenth, seventeenth, and eighteenth centuries resulted in heavy losses of ships and of lives.

Several of the European states offered substantial premiums for the discovery or invention of an adequate method of determining longitude. In 1598, Philip III of Spain offered a prize of 1,000 crowns. About the same time, the States General of Holland are said to have offered 10,000 florins for such a discovery. The Republic of Venice promised rewards to a successful inventor. Colbert offered encouragement to work in this direction, and in 1716 a definite offer of 100,000 livres (about $20,000) was made. In 1691, the will of Thomas Axe, subject to serious incidental restrictions, offered a legacy of £1,000 to the discoverer of marine longitude. In 1714, Parliament authorized by statute three prizes for a method of determining longitude, graded in amount according to the degree of accuracy achieved:

£10,000 for a method accurate within 1 degree of longitude.
£15,000 for accuracy within 40 minutes.
£20,000 for accuracy within 30 minutes.

The administration of this statute was entrusted to commissioners known as the Board of Longitude. This board continued in existence from 1714 to 1828, disbursing during that period about £101,000. This was the largest expenditure made by any European state towards the solution of this particular scientific problem, and, as it played a notable part in the stimulation of work on the marine chronometer in England, it must be regarded as a significant influence.

The persistent striving towards this particular accomplishment is an interesting indication of the degree to which invention can become a deliberate volitional activity. The desirability of this specific mechanical application was perceived early in the sixteenth century: about 1660, conscious efforts were made by Huygens and Hooke to perfect both the pendulum clock and the spring-driven watch. Though these inventors made important progress their achievements fell short of the goal by significant margins. No adequate timepieces were made until almost a full century after the notable inventions of Huygens and Hooke, and not before another generation had passed was the chronometer perfected and available in sufficient numbers to enter into practical use. The obstacles to the achievement of the desired end were those that are always present: the difficulty of conceiving or contriving things that are really new, the number of specific innovations

requisite, the number of critical problems involved in the effective application of the new principles, and the delicacy of the problems of design. Under such circumstances, considerable intervals of time are likely to occur between the various essential inventions, and critical analysis of detail is itself a time-consuming process. There is nothing in the historical record to support the thesis that real innovations can be accomplished by any purely rational process subject to direct voluntary control.

The importance of details of design is notably illustrated by Earnshaw's experience with the first dozen watches made upon the plan that has in general dominated chronometer construction ever since. They were always stopping, and Earnshaw was obliged to alter them at his own expense. The defect proved to be in the proportions between the impulse roller and the escape wheel. "The impulse roller was only about one-quarter of the diameter of the escape wheel, while about 120 degrees of its circumference intersected the path of the escape-wheel teeth. If the vibrations of the balance were reduced below this amount by external motion, the watch would stop."

Accordingly, Earnshaw after bitter experience of this fault, made the impulse roller half the diameter of the escape wheel, reducing the intersection, and the consequent minimum arc of the balance to about 60 degrees.

The effective history of marine timekeepers began with the construction of Huygen's pendulum-regulated marine clock, in 1661, and with the projects of Robert Hooke which resulted in an effective balance spring for the spring-driven movement. Huygens executed a clock which was tried at sea, but despite some favorable results in very quiet weather the operation of the instrument was hopelessly inaccurate in rough weather and in 1674 Huygens recognized that the variation of gravity at different latitudes would be an insuperable obstacle to the use of the pendulum at sea. Despite this early recognition of the futility of the pendulum, several attempts were subsequently made on this principle. In 1720, a Dutch clock maker, Messy was awarded a prize by the Academy of Sciences at Paris, for a statement of means of using the pendulum at sea. Henry Sully, an Englishman living in France, made a marine clock which was finished in 1724; but on being subjected to various severe tests it was regarded as unsuitable for marine use. In 1726, J. B. Dutertre made a clock with two pendulums, and with him the series of marine clocks comes to an end.

Though Hooke invented the spring balance which was designed and in fact destined to be the basis of a marine time keeper, he lost interest in the matter after the failure of his attempts to form a syndicate to exploit the invention, and never himself constructed a timepiece involving that device. Huygens became interested in this type of timekeeper after 1674, and did considerable work with the balance, but the full details of his work in this direction were never published. The balance spring was quickly applied to pocket watches, much to their improvement, but before it could become the basis of an instrument of precision it was necessary to make important changes in the escapement and to provide for the complex influences of the variations of temperature upon the length and elasticity of the balance spring. All early provision for regulation was based upon alteration in the effective length of the spring; the usual mechanism (shown in Fig. 108) consisted merely of a lever by which two curb pins could be moved nearer to or farther from the fixed end of the spring. This device is still employed on common watch movements, but it is not sufficiently delicate to meet the requirements of an instrument of precision.

Although the problems of clock and watch movements were different in many ways, the rapid improvements in the clock in the early eighteenth century probably explain the striking successes of Harrison, Pierre le Roy, and Ferdinand Berthoud in the middle of the century following a long series of failures. The accomplishments and rewards of these three inventors were strangely different. Harrison finally received the $20,000 prize offered by the British government, in addition to £1,000 granted earlier to assist in building the second and third of his chronometers. But though Harrison achieved precision and bore the brunt of convincing the British world that longitude could be determined by means of a chronometer, the mechanical features of his timepieces were not adopted. Kendall and Mudge owed much of their interest to Harrison's achievement and were indebted to him, also, for many initial concepts, but their work and that of others rapidly diverged from that of Harrison. His innovations had been corrective and supplementary to the primary parts of the ordinary watch movement of his day: the famous number four movement was a masterpiece of refinements in execution, but it merely nullified the defects of the primary operative parts.

The actual development of the chronometer was based upon the work of Pierre Le Roy, whose studies led to fundamental

changes in the principles and design of marine timepieces. Le Roy discovered that balance springs would produce truly isochronous vibrations only at specific lengths. He said:

". . . there is in every spring of sufficient extent, a certain length where all vibrations whether large or small are isochronous; . . . if having found this length, you shorten the spring, the large vibrations will be quicker than the short ones; if on the contrary, you lengthen the spring, the small arcs will be

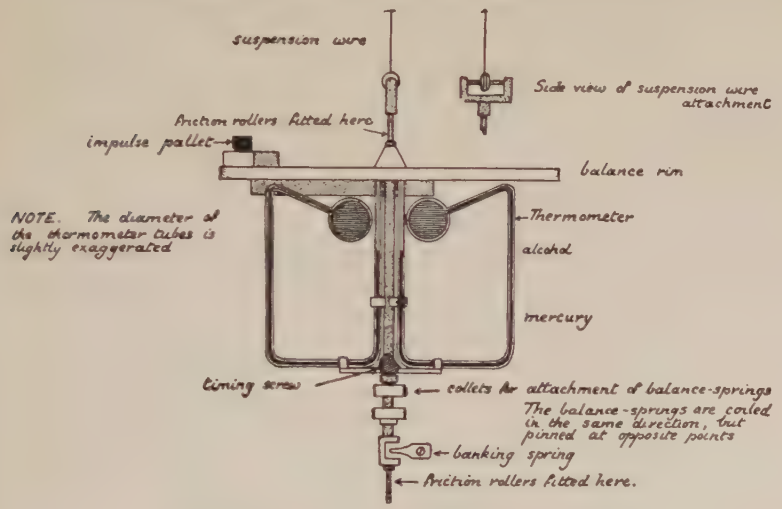


FIG. 109.—Le Roy's compensation balance.

described in less time than the large ones."[245] According to this principle, the attempt to regulate the balance by altering the length of the spring would lead to new irregularities. Le Roy thus concluded that regulation must be based upon alterations in the resistance offered by the balance. He devised compensating adjustments of two forms, a mercurial thermometer and a bimetallic balance of steel and brass. He esteemed most highly a mercurial thermometer in which a rise in temperature caused a movement of the mercury towards the center of the balance. The general features of this device are shown in Fig. 109.[246] Alcohol is used in the upper part of the thermometers in order to secure greater movement in the mercurial columns. His laminated bimetallic balance is closer to the forms now used. He also provided a new

[245] GOULD, p. 88.
[246] GOULD, p. 89, Fig. 21.

type of escapement, designed to interfere as little as possible with the vibration of the balance. This was the first detached escapement, and though the form he used did not come into general use, it was sound in design and in some respects superior in conception to the spring detents finally perfected. These two concepts—the compensated balance wheel and the detached escapement—were the fundamental supplements to the balance spring.

Although his chronometers bore up well under marine tests, Le Roy was dissatisfied with results, lost interest in the problem, and abandoned all work on the chronometer. He obtained his results by devising new mechanisms which eliminated the defects of the watch movement and thus "evolved by sheer force of genius, a time keeper which contains all the essential mechanism of the modern chronometer."[247] The chronometer tested was not completed until 1763, following Harrison's famous number four by four years; but the plan for the chronometer was conceived as early as 1754, and a movement was completed by 1756. The concept thus preceded the completion of Harrison's number three by three years and a movement was actually executed prior to the completion of either of Harrison's primary accomplishments. Priorities are thus a rather complex problem.

As Le Roy published a detailed statement of his experiments and designs, there was no obstacle to the use of his ideas, but the extent of the direct indebtedness of Arnold and Earnshaw remains uncertain.

The third of the group of mid-century inventors, Ferdinand Berthoud began his work as early as 1754. His early work was inferior in conception and execution to that of either of his rivals, but he persisted in his efforts and made about 70 chronometers before his death in 1807. He was largely instrumental in establishing this mode of determining longitude in France, and many of his innovations were of substantial importance. He has claims to the invention of the spring-detent escapement, and though Arnold has an early patent to his credit, it is by no means clear that his accomplishment was, in fact, prior to that of the noted French watchmaker.

The designs of the chronometer were perfected and simplified by John Arnold and John Earnshaw. Their work resulted in reducing the compensated balance and the spring-detent escapement to stable form. Although Arnold's work was important and both

[247] GOULD, pp. 86, 90.

claimed priority in both inventions, Earnshaw's designs were superior and were the basis of the parts of the modern chronometer. Earnshaw's balance is shown in Fig. 110 beside the modern

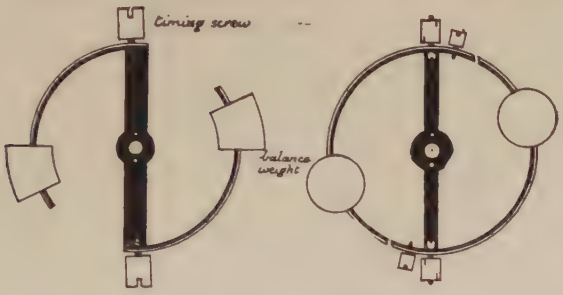


FIG. 110.—Earnshaw's balance and the modern form.

counterpart.[248] The arms are made of strips of brass and steel. Earnshaw cut out a disk of solid steel, ran molten brass on its edge, and then finished the wheel on the lathe, cutting out the

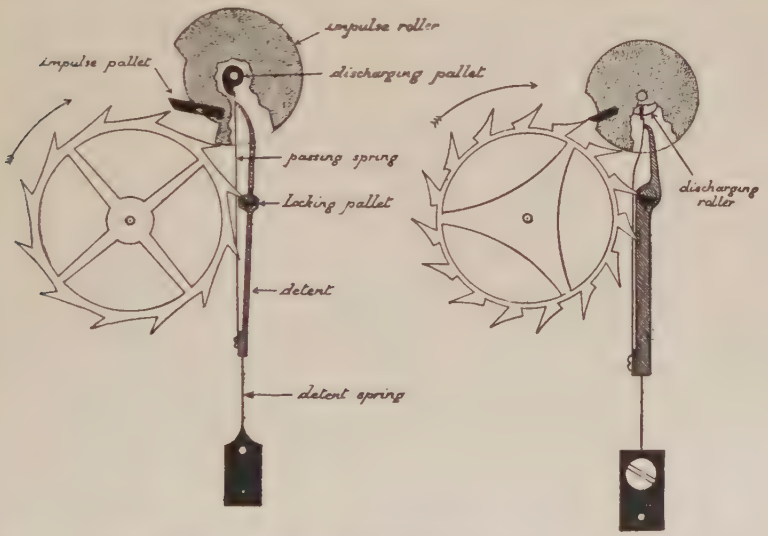


FIG. 111.—Earnshaw's spring detent escapement and the modern form.

segments between the arms and the cross-bar and similarly the sections of the arms. Earnshaw's escapement is even more distinctive. Its early form is shown in Fig. 111,[249] together with a

[248] GOULD, p. 118, Fig. 33.
[249] GOULD, p. 118, Fig. 34.

modern type that differs slightly from the later escapements made by Earnshaw after refinements in design had proved to be necessary. The requirements of the chronometer escapement are that the balance should not be subject to any interference and further it should require no oil. If oil be used there is danger lest it become thick in a long interval of continuous operation, making the action of the escapement irregular. The spring detent has thus secured a commanding position as the regulator of instruments of precision. The action of the device will be readily followed. As the balance swings in the direction of the arrow, the discharging pallet pressed on the passive spring, bends the detent spring and unlocks the escape wheel. The tooth shown immediately under the impulse pallet then strikes the pallet, which has previously swung forward, gives impulse, and disengages as the pallet swings clear. The tooth of the escape wheel next ahead locks on the locking stone, the detent having been brought back into position by the detent spring. On the return swing of the balance, the discharging pallet passes the passive spring, which opposes only trifling resistance to motion in this direction, as it is not supported by the end of the detent. The designs once perfected, methods of manufacture were developed suited to the production of chronometers in significant numbers. Upwards of a thousand satisfactory instruments were turned out in a few years so that their general introduction was assured. As the stabilized designs were not achieved until late in the decade 1780–1790, the final accomplishment represented the efforts of five men over a period of about 60 years.

The conditions prescribed in 1714 for the first prize offered by Parliament required the chronometer to achieve accuracy within 30 minutes of longitude in a voyage from Great Britain to the West Indies. Assuming a voyage of 6 weeks, "the error of the time keeper must not amount to more than 2 minutes in that period, or approximately 3 seconds a day." The chronometers of Harrison, Le Roy, and Berthoud all attained a higher degree of accuracy than was required by the Parliamentary test. Harrison's number four was found to be 5 seconds slow upon arriving at Jamaica, amounting to an error of 1¼ minutes of longitude, or about 1⅓ statute miles.[250] Two of Le Roy's watches were taken on a coasting voyage of 46 days in northern waters: the first watch showed a total error of 38 seconds in time, equivalent to 6½ statute miles at the equator; the second showed 7¼ seconds error in time, or less

[250] Gould, p. 56.

than 2 statute miles at the equator.[251] The performances of Le Roy's watches, thus, were not satisfactory, and they were likely to be injured by rough usage. The performances of Berthoud's number eight were not so good, though they were well within the limits specified by the Parliamentary test. Trials made in 1768–1769 showed for voyages of 42, 25, and 44 days, respectively, errors of longitude amounting to 4¼ minutes, 15½ minutes, and 7¼ minutes. The best record of this timepiece was an error of 4 minutes of longitude on a voyage of 68 days. Of the early chronometers, Harrison's was thus more sturdy in construction and more accurate in performance, despite the superiority of Le Roy's conceptions. The full development of the innovations begun by Le Roy, made the chronometer a much more accurate timepiece than would have been supposed possible. These accomplishments, however, can best be measured in terms of the tests made at the Greenwich Observatory. To facilitate comparison with the tests that have been currently made since 1840, Gould has computed the eighteenth-century tests according to the modern formula. These tests are expressed in terms of a trial number. This is obtained by taking weekly sums of the daily rates of gain or loss, during the 29 weeks of the trial. To the difference between the greatest and least weekly sums is added twice the greatest difference between two consecutive weeks. The formula is designed to give emphasis to the two phases of the problem of navigation, the long, continuous voyage and the short voyage. Obviously, the good chronometers achieve a low trial number. The trial numbers of several early chronometers are given on page 292.

The performance of Mudge's number one is not readily explained: at all events its qualities could not be reproduced even by its maker, for the "green" and "blue" chronometers were made later on designs that were intended to be improvements. The number one was closely similar to Harrison's number four, but was an extraordinary piece of workmanship. Apparently, the change to principles of construction that were mechanically superior was not immediately productive of better results. After 1800, the tests show trial numbers below 20, but performances disclose no steady improvement until after 1863 when the trial numbers fall definitely below 20. Some improvements are indicated in the latter part of the nineteenth century, when trial numbers as low as 9 are achieved. Most of the tests range between 12

[251] GOULD, p. 92.

TRIAL NUMBERS OF VARIOUS CHRONOMETERS

(Computed by the current formula[252])

	Chronometer number	Trial number
Harrison	1	1,139.0
Harrison	2	690.9
Harrison	3	130.5
Harrison	3	428.6
Harrison	4	124.4
Kendall	1	138.0
Kendall	2	155.0
Mudge	1	11.73
Arnold	36	44.91
Mudge "Green"	..	58.12
Mudge "Blue"	..	39.39
Earnshaw	1	25.57
	2	30.42

and 18. We may say then that Earnshaw's early chronometers were as good as many or even most of the chronometers down to 1850–1860, but inferior to the best of those tested in the first half of the century and distinctly inferior to the average of the latter half of the century.

[252] GOULD, p. 259.

Chapter XI

THE PRODUCTION AND APPLICATION OF POWER: 1500–1830

I

The development of the turret windmill in Italy towards the close of the fifteenth century was the last significant addition to the list of prime movers until the invention of the steam engine. The medieval period must thus be credited with all the preliminary work in the development of the low-powered prime movers, but it is probable that the sixteenth and seventeenth centuries were marked by a substantial development in the range and character of the uses of power. The invention of printing and the development of the illustrative arts of engraving and wood cutting resulted in such a substantial change in the character of the evidence of the state of technology, that it might be urged that the more abundant and better pictures of machines represent progress in drawing rather than in engineering. But when every allowance has been made for the inadequacy of the record of the fifteenth century, there is evidence of notable inventive work and of considerable ingenuity in extending the application of familiar devices and principles. Leonardo da Vinci's career marks the transition. Before his day, mechanical engineering was merely an incidental feature of work in the building trades, the heavy metal trades, and a group of military activities that were being extended by the development of gunpowder and artillery but which for the most part were a direct continuation of a tradition reaching back to antiquity. Fifteenth-century drawing and writing on mechanical subjects was confined to the military engineers and architects, with the former largely preponderant. Exclusive of Leonardo, seventeen technicians of the fifteenth century left Ms. treatises or collections of drawings. The Germans were all identified with military affairs. One of the Italians, Giuliano di San Gallo, was notable as an architect and some of the others may have been identified with architecture. Only one of these

works was printed during the fifteenth century—the treatise of Robert Valturius on "Military Affairs," which was first printed some years after his death and frequently reprinted thereafter. Although Leonardo gave some attention to fortress construction and to artillery, these matters were secondary rather than primary, and the interest in the application of mechanism to industry predominated. The work of Leonardo also created new bonds between work in pure science and engineering, which were never again completely broken.

The treatises of the sixteenth century, concerned directly or indirectly with mechanics and mechanical apparatus, fall into three groups. There are a few treatises dealing with general science, represented by Jerome Cardan's encyclopedic works (1550–1557), and Gianbattista della Porta's work, issued first in 1558 under the title, "Natural Magic," and greatly expanded in 1589. The portions of this later work on pneumatics were further developed and expanded in 1601. Both of these writers were significantly influenced by Leonardo; to such an extent, in fact, that they constitute part of the mechanism by which the work of Leonardo was built into the effective literary tradition of these subjects. The century also produced two notable treatises on metallurgy, by Vanucio Biringuccio (1540), and by Georg Bauer, more commonly known under the Latin form of his name, Agricola (1556). Of the two, the latter is the more notable, both as regards the subject itself and most particularly in respect of the incidental record of contemporary mechanical technique, for Agricola's treatise is profusely illustrated with carefully prepared woodcuts.

Besides these works in which illustrations are definitely subordinated to text, there are a number of works which consist of plates with the barest descriptive text. The drawings of Jacques Besson who died in 1568 were published at Lyons in 1578 with a brief Latin text. A larger set of plates was published with French and Italian text by A. Ramelli (1588). The papers of Strada (1523–1588), an Italian in the service of the Emperor, were published with a German text in 1618 and 1629. At the close of the century Buonaiuto Lorini issued a treatise on fortification which marks a notable break with medieval traditions. The important treatise of Zonca (1568–1602) was published after his death. All of these collections of drawings combine old and new elements, but the studies of Theodor Beck have revealed clearly a striking development of the knowledge of the elements of machines and notable increase in the skill

with which they were being adapted and combined to meet new needs.

Ramelli and Strada reflect many influences that can be traced back to Leonardo, and seem to give expression to the work of a considerable group of Italians. Beck is inclined to believe that we should attribute large significance to the work of this "school" of Italian engineers. They laid the foundations for the modern science of applied mechanics. Their work is to be distinguished from earlier work because it is more definitely conscious of its ends and because it is more general in scope. Like Leonardo, they were working deliberately towards a generalization of the use of power, and though the sources of power at their command were limited they clearly reached a new conception of the potentialities of mechanism. Their efforts ultimately led to the successful exploitation of new sources of power, which gave a wholly new significance to many mechanical devices that had originally been developed in conjunction with such small units of power working at such low potencies that they were scarcely removed from the category of hand work.

There is no contemporary evidence of the amount of work that could be accomplished by the types of prime movers used in the sixteenth century. Until the late seventeenth century, no attempts were made to determine the amount of work done and the amount of power lost through friction, and the early studies were without satisfactory result. Signal progress was made during the eighteenth century and towards its close important results were achieved by Smeaton, Watt, and Evans. But even these studies were limited in scope so that we have little effective description of the flour mills, except in terms of their hourly output, and no specific statement to afford any direct clue to the amount of actual work performed by a horse-operated mill. The approximate gradation of the various sources of power can, however, be worked out from modern coefficients. There are two figures given for the amount of power required to make flour. Tests made by Navier, Poncelet, and Hachette indicated that in grinding 1 hectoliter of wheat in an hour a force of the intensity of about 3 horsepower must be exerted continuously.[253] In English units, this would be equivalent to 0.945 horsepower hours per Winchester bushel, or 0.985 horsepower hours per bushel of the United States standard. Similar tests by Fenwick, in England, made unfortu-

[253] D'Aubuisson, p. 448.

nately with rye, yielded the result—0.43 horsepower hours per bushel. The performances of steam engines at Albion Mills in 1786–1789 were computed at the rate of 0.992 horsepower hours per bushel of wheat.[254] Fenwick's figure seems hardly in line with the others, probably because a coarser product was being made. The other figures afford a clue to the size of flour mills and enable us to secure some notion of their relation to other power devices. The various prime movers stood to each other in about the rank indicated in the following table:

RATINGS OF THE VARIOUS PRIME MOVERS[255]

	Power Exerted, Horsepower
Man working a pump	0.036
Man turning a crank	0.04 –0.078*
Man pushing a capstan bar	0.047
Horse turning a gin at a walk	0.267–0.578*
Various 18-foot overshot wheels	2 – 5
Post windmill	2 – 8
Turret windmill	6 – 14

* Working in relays yields the higher rate.

It is, of course, especially difficult to form any notion of the potentialities of water wheels, but a number of references by Evans and Smeaton indicate clearly that flour mills run by water power seldom ground more than 5 nor less than 2 bushels of wheat per hour. The windmills described by Bennett and Elton are perhaps more indicative of the relative performance of the two types. The mill ratings of the table are based on such data. Fifteenth-century mills would scarcely have been as good, as there were some new refinements in construction. The performance of the nineteenth-century horse was undoubtedly better than anything possible prior to the improvements in stock breeding. The modern figures, however, assume rates of working that could be maintained for 8 hours, though in the earlier period it was customary to work men or animals in relays, with fairly short shifts.

Desaguliers, in the early eighteenth century, assumed that a horse could exert five times as much energy as a man, but for

[254] NICHOLSON, "Operative Mechanic," p. 149; FAREY, "Steam Engine," p. 516.

[255] Rankine's figures for continuous work are supplemented in the table with figures from d'Aubuisson for horses and men working in relays: D'AUBUISSON, pp. 316, 512.

somewhat shorter intervals of time. This view is not inconsistent with the later figures.

Some large overshot wheels were built in the seventeenth century for pumping, which must have exceeded by a wide margin the wheels of the ordinary flour mill, but Smeaton's comments imply that the increase of weight in large wheels reduced their efficiency so that for the most part wheels were most effective when they did not exceed 20 feet in diameter. Where the power requirements were greater and the water was available, the number of wheels could be increased. The famous machine at Marly, which worked the fountains at Versailles, was driven by 14 water wheels which delivered at least 75 horsepower in actual work.

Although these early prime movers were small, they were by no means without economic importance. In many industrial applications, the amount of power used per employee is not large. In Belgium, in 1910, relatively few industrial groups show averages of much more than one horsepower per employee.

POWER USED IN VARIOUS INDUSTRIES
(In Belgium: 1910)[256]

	Horsepower per Employee
Specific industries:	
Steel manufacture (group IV, 10)	5.05
Machine cotton spinning (group IX, 408)	2.98
Glass (group VI)	1.506
Flour mills—steam, gas, gasoline motor	4.4
General industrial groups:	
All metals (group IV)	1.59
Ceramics (group V)	0.63
Foods, etc. (group VIII)	1.91
Textiles (group IX)	1.14
Clothing (group X)	0.07
Leather and manufacturing (group XIII)	0.43
Printing (group XVI)	0.36
Industries of art (group XVII)	0.51

In the United States, a larger amount of power is commonly used, but except in the furnace industries which used a large amount of energy in the form of heat, few industries use more than 5 and many use less than 1 horsepower per employee. The industry of flour milling used an average of 21.6 horsepower per employee in 1910. The smaller flour mills of the early nineteenth

[256] Belgium, *Office du Travail, "Recensement de l'industrie et commerce,"* Vol. VIII, pp. 483 *ff.*, 1910.

century employed two or three persons, so that slightly more than 1 horsepower was used per person. This affords perhaps the most adequate standard of comparison available for judging the amount of power that could practically be furnished per employee over a long period of time. Windmills and even a small water power, such as might be utilized effectively prior to the development of the turbine, could supply a quantity of power that was genuinely significant, but there were serious limitations of cost, of availability as to location, and of constancy of operation. For many sixteenth- and seventeenth-century industries, the obstacle to the use of more power was cost and physical availability quite as much as the mechanical difficulty of applying power. The capital involved was large relatively to the amount of power generated. Competition between directly operated appliances and power-using devices was thus in favor of the use of mechanisms actuated by the workman, unless the character of the power requirement in respect of the intensity of the operative force or the form of motion made some mechanical device essential. Much early machinery was thus concerned with exchanging low intensities exerted through long distances for high intensities exerted through short distances. Important mechanical principles were frequently embodied in these essentially simple devices, but they merely supplement the direct exertion of men and animals, and had little influence upon the general structure of industry. Many operative machines were given forms which would make it a simple matter to arrange them to be driven by any prime movers capable of producing rotary motion, but until power became cheap, reliable, and generally available, there was no purpose in attempting to run them from a specialized power plant.

II

Some new demands for power had appeared, however, which exerted a positive pressure in the direction of the production of power in relatively large units. The larger towns were beginning to perceive the economy of creating a general city water supply, and the exhaustion of the easily worked minerals was making it more and more essential to carry mining to depths which lay beyond the competence of the older hydraulic devices for raising water. Toledo was furnished with water in 1526 by a complex piece of apparatus designed by the Italian engineer Juanello

Turiano.[257] Augsburg is said to have established a public water system in 1548, and other German towns followed her lead. The expense of long aqueducts was avoided by the use of numbers of force pumps operated by water wheels. A windmill was built at Gloucester, England, in 1542 to raise water into a reservoir from which the town was supplied. In 1582, pumps were built by Peter Morris (Maurice) near London Bridge to supply a portion of the city with water. The first pumping station at Paris was established near the Pont Neuf in the reign of Henri IV. It was designed to supply the palaces of the Louvre and the Tuileries. Because of a bronze plate representing Jesus and the woman of Samaria at the well, the pump works came to be called La Samaritaine. Similar pump works were installed later near Nôtre Dame. As the seventeenth century wore on, the city water works became rather common. For the most part, they presented a relatively simple mechanical problem as the water was not raised to great heights. The volume of water required was achieved by multiplying the number of pumps and water wheels up to the required standard. Mines presented a rather more difficult problem, because it was not so easy to provide relays of pumps to reach the depths requisite.

The newer power problems of the sixteenth and seventeenth centuries were concerned largely with pumps and pumping; and in this case the problem furnished a solution, for the new source of power ultimately discovered in the steam engine represents an application of mechanical and scientific principles that were developed in this field.

At the beginning of the sixteenth century, the known modes of raising water were scarcely different from those known to Hero of Alexandria. The only progress made consisted in the application of animal power and water power to an extent substantially beyond the mechanical capacities of antiquity. In practice, the old forms of the various hydraulic devices had been somewhat transformed during the course of the middle ages. To the older appliances was added the chain pump presumed to be of oriental origin, in considerable use in various forms in different parts of Europe at the beginning of the sixteenth century. The vacuum pump was used more generally than by the Greeks and Romans, but its principles were not understood any more adequately. In the analysis of the vacuum, no progress had been

[257] Beck, G. M. B., p. 366.

made beyond the achievements of the Alexandrines. It was realized that vacua could be created, but except under special conditions they would not persist. This fact was explained by the doctrine that a vacuum was abhorrent to nature, so that any vacuum created was at once destroyed by nature. The phenomena of the expansion and pressure of gasses were very incompletely understood, and the scientists of the early sixteenth century accepted the Greek view in which steam was not distinguished from air. Cardan and Porta were still thinking in terms of the four "elements," earth, air, fire, and water. Both Cardan and Porta performed experiments which involved some break with the established tradition but neither achieved results which led to any significant restatement of the older views.

The beginnings of a new theory are commonly attributed to the attempt to build a vacuum pump to raise water from a well 100 feet deep. The failure of the pump was called to Galileo's attention. He was inclined at first to explain the matter by the formula that nature's abhorrence of vacuum was, in fact, limited and not unlimited as the Greeks supposed. This explanation, however, left him still unsatisfied and he proceeded to devise various experiments. The height of the column of water that could be raised was determined exactly. He also measured the resistance required to draw a piston from the bottom of a tight cylinder. Some attempts were made to determine the weight of air. But no explicit generalization was drawn from these notable experiments. Torricelli continuing the investigation proposed to measure with mercury the resistance to a vacuum, with the presumption that the column would be one-fourteenth of the height of the column of water. These results were, in fact, secured in 1643 by Viviani. Variations in atmospheric pressure were also observed, but the final conclusions of these investigations were reached only by Pascal after some further work. Knowledge of the experiments of Torricelli was brought to his attention by Mersenne, about 1644, but the reports were vague and incomplete. Pascal proceeded to perform various similar experiments himself. The results were made public and all the phenomena were explained as specifically caused by the pressure of the atmosphere, with appropriate generalizations of the laws of pressure in both gaseous and fluid media. The most conclusive feature of the experiments to the general public was a demonstration at Pascal's suggestion that the mercury column stood at a lower level on the top of a mountain

than at its base. The actual experiment was performed by Perier, the brother-in-law of Pascal, at the Puy de Dome, Sept. 19, 1648.

Although this work afforded a comprehensive basis for a theory of atmospheric pressure, the independent work of Otto von Guericke was important. It not only established a correct general doctrine in Germany, but also involved many suggestions of substantial mechanical significance not appearing in the French and Italian

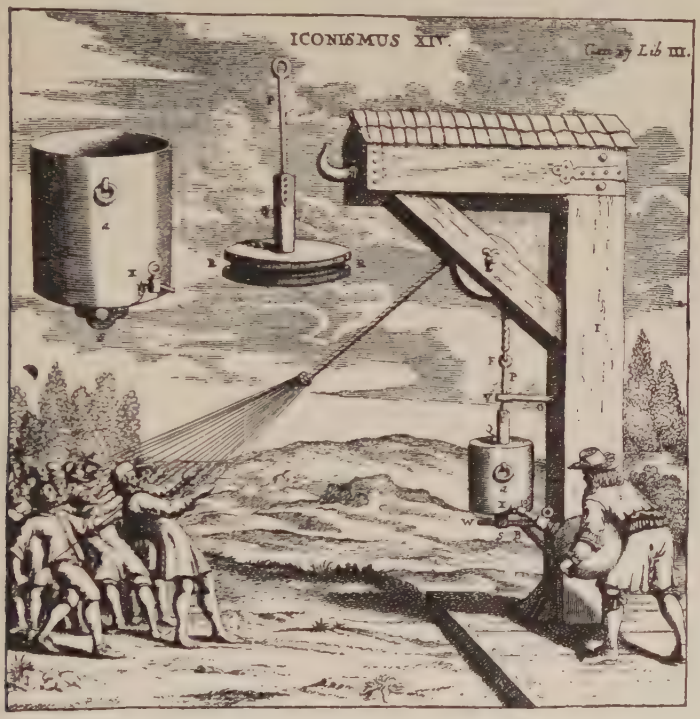


FIG. 112.—Guericke's experiment with atmospheric pressure.

experiments. Constant emphasis is laid in his writings upon the magnitude of the force of atmospheric pressure, and many experiments were arranged to demonstrate the fact. One of the earliest applications of air pressure to a piston occurs in an experiment, first performed in 1654. The arrangement of the apparatus is shown in Fig. 112.[258] The copper cylinder *A* is fitted with a piston whose head is packed with hemp or oakum to make it air tight.

[258] GUERICKE, OTTO VON, "*Neue Magdeburgische Versuche über den leeren Raum*," Translation, Fr. Dannenbaum, Leipzig, p. 78, Fig. 14, 1894.

The stop cock *X* is provided to enable the experimentors to exhaust the air. When this is done, it appears that 20 or 30 men are unable to hold the piston at the top of the cylinder. In another experiment the rope was loaded with a platform and weights, so that the pressure on the piston could be exactly determined.

The establishment of the principles of the vacuum pump led to extensive modifications of pump design, for it was possible to secure the advantages due to atmospheric pressure even if other supplementary power were necessary to complete the lift requisite. Among the later types of pump, the plunger pump possessed more than ordinary significance. The invention is attributed to Samuel Moreland, on the strength of a patent obtained in 1675. There are no specifications in the patent, but the general character of the pump is supposed to be represented by the machine set up at York Buildings in London about 1710, shown in Fig. 113.[259] The feature of this pump that proved to be significant for the future was the gland and stuffing box through which the plunger operates. Two thicknesses of cupped leather are bolted to the top of the pump cylinder and held in place by an outer plate. This detail was essential to the development of a steam engine, and, thus, although the plunger differs essentially from a piston these details of its fixtures could be carried over to other machines. In the plunger pump the prime mover lifts the plunger, whereas the water is raised by the descent of the plunger, which must, in some cases, be weighted with lead disks proportionate to the height to which the water is to be raised.

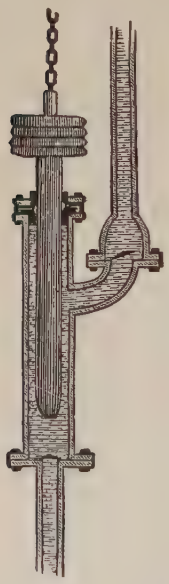


Fig. 113.—Eighteenth century plunger pump.

III

Some of the phenomena of steam were known to the later schools of Alexandria, and though no adequate distinction was made between steam and air, eolopiles and some devices for use of steam pressure were familiar to Hero of Alexandria. The eolopile was operated by the reactions set up by jets of steam escaping from vents of pipes mounted on a free axis. Many forms of them were mere scientific toys, but they were adapted to use in the temples as

[259] Ewbank, p. 272, Fig. 123.

instruments of mystification, and in many instances degenerated into mere devices for the spouting of steam for the mystification of the multitude. Hero was also familiar with some of the simpler devices for the use of the pressure of steam. No positive advance was made until the sixteenth century, and even in that period little was accomplished.

Both Cardan (1501–1576) and Porta (1538–1615) were concerned with the phenomena of steam, but though they made some progress their results were seriously qualified by misconceptions of the nature of steam which they still identified with air. Cardan, (1550), in one obscure passage, points out that a vacuum may be created by the condensation of steam,[260] this suggestion cogent as it would have been if clearly conceived, can hardly have had the significance that we might naturally be inclined to attribute to it. Porta's work on steam was rather more deliberate, and some of his experimental apparatus was highly suggestive. The attempt to measure the volume of steam by the amount of water displaced by steam pressure led him close to a positive distinction between steam and air, but he drew no decisive conclusions himself. A late contemporary, Solomon de Caus (1576–1630), with essentially similar apparatus, took this decisive step. He declared that steam is evaporated water, that upon cooling the vapor returns to its original condition. A similar experiment with mercury showed the same phenomena of evaporation and subsequent return to the liquid condition. De Caus was thus able to set down (1615)[261] a series of propositions that represented a great advance upon all previous achievements in the field of gases and their phenomena. Air and steam were thus specifically distinguished and the practical conclusion was drawn that there were potentialities in steam pressure of much greater magnitude than were to be found in air pressure.

Many writers, following the lead of Arago, have credited de Caus with the invention of the steam engine, on the strength of the alleged invention of the fountain operated by steam pressure. This is a misstatement of the actual accomplishment. The device itself was known to Hero and was scarcely different in detail from the apparatus used in Porta's experiments. The innovation consisted in the generalizations about the nature and properties of

[260] CARDAN, J., "*Les livres de Cardan,*" Rouen, Book 1, p. 19, 1642.

[261] DE CAUS, S., "*Les raisons des forces mouvantes avec diverses machines et plusieurs desseins,*" Frankfort, 1615; Paris, 1624.

steam, and these were scientific discoveries of the utmost importance. They were the principles upon which the work of Worcester, Savery, and Papin was largely based. The work of de Caus thus completed the break with the traditions of antiquity that was imminent throughout the latter half of the sixteenth century.

The continuation of the implications of de Caus' work fell to Edward Somerset, who became later the second Marquis of Worcester. Although much uncertainty still attaches to his work and the evidence is less conclusive than might be desired there is little ground for challenging the account of his biographer Dircks, though some technical writers do not accept his view. Tastes for scientific work were formed at an early date, fostered by travel and reading. There is a certain amount of internal evidence showing familiarity with the treatises of Ramelli, de Caus, and Bates. Experimental work was begun not later than 1628, when Caspar Kaltoff was engaged as mechanic and laboratory assistant. Considerable work was done at Raglan Castle in the years immediately following, and the pumping engine at the castle must have been installed at this period. Work had also been done on a considerable scale at Vauxhall, one of the properties of the family in London, prior to its confiscation by Parliament in 1643. Raglan Castle was finally surrendered to the Parliamentarians after a siege of 10 weeks, on Aug. 19, 1646. After some years spent in exile, the inventor returned to London and was imprisoned in the Tower. While in prison he set down the list of inventions and experiments he had made under the title, "A century of the names and scantlings of such inventions as at present I call to mind to have tried and perfected, which (my former notes being lost) I have at the instance of a powerful friend, endeavored now, in the year 1655, to set these down, in such a way as may sufficiently instruct me to put any of them in practice." Partly from the circumstances of its composition and partly from a desire to withhold the secrets of the apparatus, these notes are incomplete and insufficient, and though subsequently published they were not originally designed to reveal the full scope of the author's work.

The inventor was released from the Tower shortly after the composition of his "Century" was completed, and he thereupon devoted his energies to the recovery of his estates and the development of a "water-commanding" engine with which he hoped to repair his finances. An engine was finally built at Vauxhall which embodied various improvements over the engine built at Raglan

about 1630. The plan embodied the primary elements of the descriptions in the "Century." There is, however, no contemporary drawing of either the Vauxhall or the Raglan Castle engine. One may still see the empty spaces in the masonry at Raglan Castle which presumably contained the engine. Apart from this, there are merely the verbal descriptions contained in letters and the passage in the "Century." The primary features of the engine in its final form have been reconstructed in the sketch by Dircks reproduced in Fig. 114.[262] This sketch diverges considerably from notions of Worcester's engine that had been widely held at one time. It is here assumed that the machine combines the use of direct pressure of steam in raising the water from the reservoirs of the engine with the formation of a vacuum to raise the water from the source to the reservoirs. In the figure, the furnace *D* and the boiler *C* are represented by dotted lines. Steam is admitted to the boilers through a four-way cock *b* and the supply pipes *B* and *B'*. The two reservoirs *A* and *A'* are connected with the source of water by the pipes *GG'*, and are provided with outlet pipes *FF'* which unite at a four-way cock *C*. A partial vacuum is produced in the empty reservoir *A* by the condensation of a certain quantity of steam; water is then forced into the reservoir by the air pressure acting upon the surface of the water. When the reservoir is nearly filled with water, live steam is admitted through the steam valve and its pressure is sufficient to force the water out of the reservoir. When nearly empty, the shutting off of the live steam is quickly followed by condensation and the formation of a vacuum. The Worcester engine in its final form thus went considerably beyond the principles embodied in the experimental apparatus of Porta and de Caus. The combination of the use of pressure with a vacuum created by condensation opened up possibilities in the production of power which had never before been clearly apprehended.

In 1663, Parliament granted the Marquis and his heirs a monopoly of the use of the "water-commanding" engine for 99 years. The Marquis proposed to develop a waterworks to supply a considerable portion of London, and at one time visions of large profits were entertained, for he compromised a claim of £40,000 upon the crown in return for the withdrawal of the original stipulation that one-tenth of the profits be paid to the crown. The

[262] DIRCKS, HENRY, "Life, Times, and Scientific Labours of the Second Marquis of Worcester," p. 551, 1865.

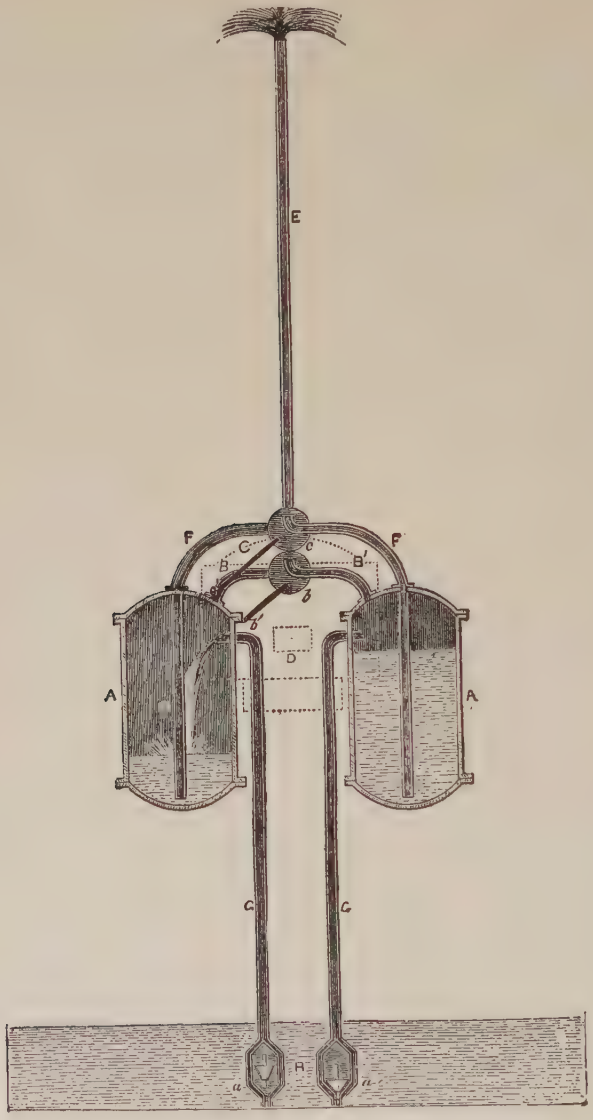


FIG. 114.—Worcester's water commanding engine.

engine is mentioned several times prior to 1670, but thereafter all notice of it is lost.

The judgment of the work of the Marquis of Worcester affects chiefly the question of the relation of his achievements to those of Thomas Savery. If the account by Dircks is accepted Savery's work must be admitted to contain little that was original. If Worcester's achievement is minimized the accomplishments of Savery are correspondingly magnified. The data are too inadequate to admit of real certainty of judgment. In any event, this type of engine whether invented by Worcester or Savery precedes the fully developed atmospheric engine and seems to lead directly to it by opening up substantial hopes of a decisive improvement in pumping by power. Savery's work on the engine came first to public notice in 1698. Demonstrations were given of fairly large working models, both privately and before the king at Hampton Court. A patent was obtained in July, 1698, which was subsequently extended to cover a total period of 35 years. The character and uses of the engine were further described in 1702 in a pamphlet under the title "The Miner's Friend." Even assuming that the general principles of the machine were, in fact, taken from the Marquis of Worcester, Savery's work involved considerable development of details and above all an extension to the field of practical use.

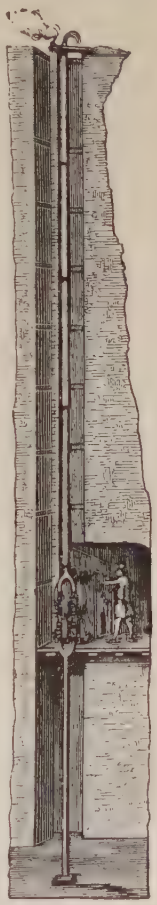


FIG. 115.—Savery's engine in a mine.

The general layout of the engine in a mine is shown in Fig. 115.[263] As the water was brought into the reservoirs by the action of air pressure on the surface of the water against the vacuum created by condensing steam, the whole apparatus must needs be located near the bottom of the shaft. The draft created by the fire improved the ventilation of the mine, and new practices in that field soon followed. This limitation of the pumping engine was, however, of serious consequence, because any failure of the engine would lead to the drowning of the pump as well as the mine

[263] GALLOWAY, "Steam Engine," p. 64, Fig. 17.

and once put out of operation no easy method of relief was available.

These engines, too, became dangerous when set to heavy tasks. In such cases the pressure required proved to be greater than the boilers then constructed could bear and boiler explosions were feared with good reason. There is no record of the building of such engines in more than one mine, though several engines were built to provide country houses with water. For light duty, the engine was thus of some utility, but the superiority of the Newcomen engine prevented any significant development.

This line of development must be associated with a somewhat larger background, involving as it does the principle of air pressure working on a piston head against a vacuum created by the condensation of steam. It is not a development out of the fountain engine of Worcester and Savery, but an alternative mode of securing power, in which steam played an auxiliary role. Apart from the experiments of Guericke, some of which were known in England as early as 1657, there was considerable experimentation with pistons as media for the utilization of air pressures. Dircks credits the Marquis of Worcester with some experiments with pistons, on the basis of proposition number 99 of the "Century," but it must be admitted that this is sheer inference: by no means impossible, but unsupported. Hautefeuille (1678), Robert Hooke (1678), and Samuel Moreland (1681) are credited with experiments on evidence that likewise is inconclusive. Huygens and Papin both made trials of a piston as a means of utilizing atmospheric pressure, but they proposed to create the vacuum under the piston by exploding a small charge of gunpowder. On the whole, there was enough to suggest the problem and to set the stage, as it were, but certainly no conclusive result prior to the work of Newcomen. The invention of the atmospheric engine in this form was the greatest single act of synthesis in the history of the steam engine and must be regarded as one of the primary or strategic inventions. The important work of Watt and his contemporaries was critical rather than synthetic and though new devices had to be invented they are, after all, improvements of the Newcomen machine, which can scarcely be rated as greater inventive achievements.

It is particularly unfortunate that the evidence on Newcomen is so scant and that the near-contemporary accounts are so contradictory and inadequate. Under the circumstances there is scarce any feature of Newcomen's career that is really settled beyond doubt. At present, the best account is given by Dr. Robison

(1797) on the basis of notes in the papers of Robert Hooke at the Royal Society. Some doubt has been cast upon the authenticity of these notes as they were not known to the custodians of the manuscripts of the Royal Society in 1880. It does not appear, however, that any real search was made, and even if the papers have actually been lost there seems to be no ground for doubting the statements of Dr. Robison, who was conscientious in the collection of historical data. In addition to these papers, there are two copies of an engraving of the engine "invented by Mr. Savery and Mr. Newcomen" and "built by the latter" near Dudley Castle in 1712. The engraving is dated 1719, so that the plate is not presumed to represent the engine in its original condition. These materials have been most competently handled by Galloway.[264] In 1925, a drawing of an engine was discovered, dated 1717. The plate is the work of Beighton, and may afford an explanation of the attribution of certain improvements to that engineer.

Though Newcomen was country bred and spent most of his life in the country, he was kept in touch with the scientific work of the day by his correspondence with Robert Hooke of the Royal Society. During the last decade of the seventeenth century, Newcomen became interested in Papin's scheme of operating pump pistons by air pressure transmitted through pipes from another set of cylinders operated by a water wheel. Hooke urged him against this project, but suggested the possibility of operating the piston by creating a vacuum under it by the "speedy" condensation of steam. What stage Newcomen had reached with his work at the death of Hooke in 1702–1703 we do not know. It is alleged by some that he applied for or even received a patent in 1705, but there is no record of any application or grant. The two distinct plates of the engine frequently published under the date 1705 are wholly conjectural, and there is evidence of the near contemporary Switzer to cast further suspicion upon all of these allegations about the period 1703–1710. We may be fairly certain of only one fact of this stage of Newcomen's career. At some time subsequent to Savery's patent, Newcomen and Cawley (Calley) joined forces with Savery, and agreed to make engines under that patent, which was so loosely phrased as to include Newcomen's schemes.

The first atmospheric engine, which we know of, was built near Wolverhampton in 1712. Galloway identifies this engine

[264] Galloway, "Steam Engine," pp. 52–56, 78–134.

as the engine near Dudley Castle shown in the engraving of 1719, but he intimates that the mechanism of the engine was perhaps significantly developed after erection so that the drawing represents its fully developed state. The points most in doubt are the method of effecting condensation, and the method of operating the cocks and valves. Galloway's position is inconsistent, as he uses the print as evidence for the early application of a mature arrangement for working the valves and cocks, but admits that there was no injection jet in the engine in its early form. We are thus merely in a position to say that the first engine was built by Newcomen and his associates and speedily brought to a state of substantial maturity, either before or shortly after it was put into general operation. The print discovered in 1925, however, decisively settles Newcomen's invention of the plug rod and valve gear.

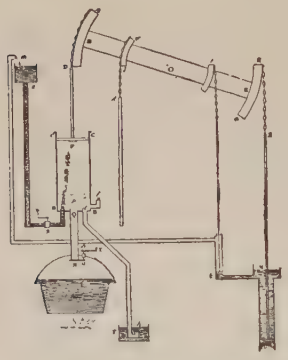


FIG. 116.—Primary features of the Newcomen engine.

The general features of the engine are shown in Fig. 116.[265] All details have been suppressed, so that we have merely a schematic diagram representing the general principles of operation. One of the conspicuously new parts of Newcomen's machine was the balance beam, or working beam, which was retained for generations in the condensing engine. To the ends of this beam are attached the piston and the pump rods, counter-poised in such fashion as to make the pumping end considerably heavier than the piston end of the beam. Nearer the center are suspended other rods: at E a rod which works a small pump which feeds the injection reservoir; at ϕ a rod which carries attachments to operate the valves.

The natural position for the engine when at rest is shown in the figure, for the counter-poises would quickly raise the piston to this position if air were admitted to the cylinder through the valve f.

[265] ROBISON, "Mechanical Philosophy," Vol. II, Plate I, Fig. 7. Most of the plates of the alleged engine of 1705 closely resemble this diagram, and may have been taken from it. Dionysius Lardner, writing in 1836, gave wide currency to this figure as an illustration of the engine of 1705. An entirely distinct conception of the alleged engine of 1705 is given, without citation of source, by EWBANK, "Hydraulics," p. 465, Fig. 196.

If we suppose that the engine is to be started, we must presume that for the moment no jet of water is injected into the cylinder. All valves are closed and the cold cylinder is filled with air. Steam is admitted by opening the valve *N* by the lever *T*. The air in the cylinder is expelled through the valve *f*, which opens to upward pressure. As the cylinder is cold, much steam is condensed, but as new steam enters from the boiler, the cylinder is soon heated and filled with live steam. The injection cock is then opened, and the spray of water condenses the steam rapidly. Air pressure acts in a small measure on the bottom of the cylinder, so that, in fact, these cylinders were fastened to resist upward pressure but as condensation proceeds the pressure of the air on the piston forces it down, and as the process of condensation continues the descent of the piston is accelerated. Friction and the effect of the counter-poises ordinarily reduced the effective pressure on the piston to 7 or 8 pounds per square inch, though the total pressure amounts to 14.7 pounds. Once the engine is in operation, the rise of the piston is accompanied by a slightly different set of phenomena. When the piston has reached the bottom of the cylinder, the injection jet is closed and the steam valve is opened. The first puff of steam clears the cylinder of any vapor remaining and creates sufficient pressure to allow the water of condensation to flow off freely. The piston rises by reason of the counter-poises as rapidly as steam flows in; for there is sufficient weight to lift the piston but not enough to create a vacuum. Accordingly, the rise of the piston and the filling of the cylinder with steam are concurrent, though the steam does not exert any active force against the piston.

The engraving of the engine of 1712 (1719) shows a machine that provides automatically for the opening and closing of these valves and for condensation by the injection jet. The recently discovered engraving of 1717 is similar in most details. There is thus ground for presuming that the first large engine was complete before it left the hands of its inventor. The detail of the valve mechanism and the plug rod to control them need not detain us. The general appearance of the engine with its shed is shown in Fig. 117.[266]

This invention marks the effective beginning of the utilization of the new sources of power with which scientists and inventors had been struggling actively for about a century. Although the active source of pressure was the atmosphere, the actual operation

[266] GALLOWAY, "Steam Engine," p. 114, Fig. 23.

turned upon the production of steam and practically all the engines were coal burners. The engine was safe, even for the kinds of boilers that were then available:

"The boundaries to the power of this machine are not the strength we can give to boilers and cylinders to resist internal

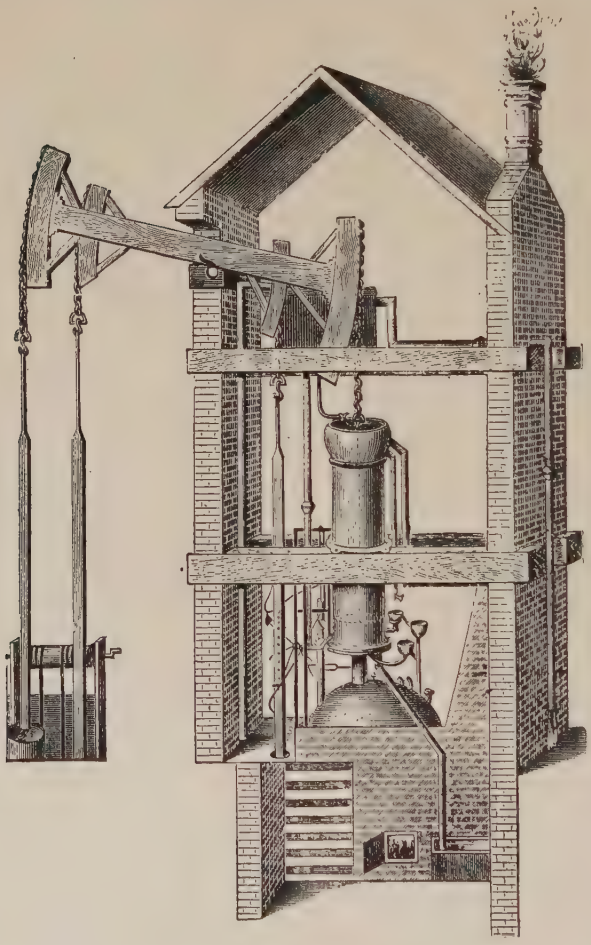


FIG. 117.—Newcomen engine, 1732.

pressure, but the dimensions to which we may find it practicable or expedient to make them, and the other parts of the machine, such as the working beam, or great lever, and its appendages."[267]

[267] ROBISON, "Mechanical Philosophy," Vol. II, p. 69.

The engine of 1712 had a cylinder 21 inches in diameter, 7 feet 10 inches long, and made 12 strokes per minute. If later formulæ are applied, this would indicate about 7 horsepower available for effective work. The reports of water actually raised indicate 5½ horsepower. The effective practical limits of size were reached when the cylinders were 72 inches in diameter. Smeaton reports having seen engines with cylinders 75 inches in diameter, but they were rare. A list of 99 engines was compiled by him in 1769 with a view to studying the best proportions of the engines. The data of the list are embodied in the following table, though in many cases the diameter of the piston is not given, and about one-third of the engines thus do not appear in the table.

SIZES OF ATMOSPHERIC ENGINES LISTED BY SMEATON IN 1769

Diameter of the Cylinder	Number of Engines
13 to 29 inches	11
30 to 45 inches	25
46 to 60 inches	20
61 to 75 inches	11

The Long Benton colliery engine built in 1772 with a cylinder of 52 inches was rated at 40½ horsepower: the Chasewater engine of 72-inch cylinder was rated at 76½ horsepower. These engines of Smeaton's represented various improvements in design so that they would scarcely be representative, but they indicate with some adequacy the approximate limitations of the power to be derived from this type of engine. The smallest engines were somewhat more powerful than a single water wheel, and fully equal to the smaller windmills. In 1717, Beighton constructed a table of the pumping performance that might be expected of engines of various sizes. He assumed an effective pressure on the piston of 8 pounds, 16 strokes per minute, and a 6-foot stroke. With larger boilers 20 or 25 strokes per minute might be expected in cylinders 7 or 8 feet long. With these assumptions the following approximate ratings on page 314 would be given to engines of stated size.

There can thus be little doubt but what the medium and larger-sized engines considerably exceeded in power any single unit of the earlier prime movers. No such amounts of power were previously obtainable without coupling several water wheels together. Smeaton, for instance, reports a power plant in Cornwall consisting of ten 20-foot water wheels set one over the other to utilize a stream with a high fall. Such a combination would yield a substantial

PRESUMED RATING OF VARIOUS ATMOSPHERIC ENGINES

Diameter of cylinder	Net horsepower	
	At 16 strokes of 6 feet	At 20 strokes of 8 feet
30 inches	16	27
40 inches	28	47
50 inches	44	74

amount of power, but only some such combination could be compared to these Newcomen engines. They were wasteful of energy, to be sure, but they burned the lowest grade of coal, and at the mines, fuel was cheap. So cheap, in fact, that engines of this type continued in use as late as 1830. Newcomen thus satisfied effectively the one keenly felt demand for cheap power in relatively large units.

Although the motion of the beam was not ill suited to the production of rotary motion by means of crank attachments that were well understood, no success was actually achieved because the engine in this form exerted effective work only on the down stroke of the piston. A single-acting engine of this type could not, in practice, be used as a source of rotary motion, though attempts were made and a patent was issued to Wasbrough in 1779 which was a serious obstacle to Watt.

IV

The work of Watt on the engine was predominantly scientific and critical. Significant innovations were involved, but they supplied new parts to an existing whole. In a strict sense, therefore, they were a part of the process of critical revision and study of an existing machine rather than a new composition. Nevertheless, it is a sound instinct that rates the achievement as a strategic invention. The story of his conception of a separate condensing chamber has already been told. Repairs to be made on a model of a Newcomen engine attracted his attention to the engine, and studies upon the losses of heat through the cooling and heating of the cylinder brought home to him the importance of comprehensive modifications. The primary concept of the condensing chamber came to him on his Sunday walk. The following day he

proceeded to test the idea in the laboratory and the apparatus shown in Fig. 118[268] was set up (1765). For the steam cylinder and piston, he employed a surgeon's large brass syringe, $1\frac{3}{4}$ inches in diameter and 10 inches long. For convenience the usual position of the cylinder in Newcomen's engine was reversed, and the piston was loaded with a weight. To clear the cylinder of water, the rod of the piston was drilled and fitted with a valve at its lower end (not shown in the figure). A condensing chamber *G* was made of tin and immersed in a tank of cold water. Special provision had to be made for clearing this chamber of air and water, as there would never be any live steam under pressure to discharge such a function: a small hand pump *K* was thus added to the apparatus, steam was led from the boiler to both ends of the cylinder. When steam had been produced, the valve to the condenser and the steam valve to the bottom of the cylinder were closed and the steam valve to the top of the cylinder was opened. The air in the cylinder was expelled through the valve in the piston rod and around the condenser valve. The piston in the condenser pump was then drawn up producing a partial vacuum in the condenser. The upper steam valve was closed; the condenser valve and the lower steam valve were opened. The steam in the upper part of the cylinder flowed into the condenser and was condensed. The live steam on the lower side of the piston became active against the vacuum and in the model raised a weight of 18 pounds, indicating an effective pressure of about 13.6 pounds per square inch. The model was thus highly efficient, and the soundness of the fundamental principles decisively demonstrated.

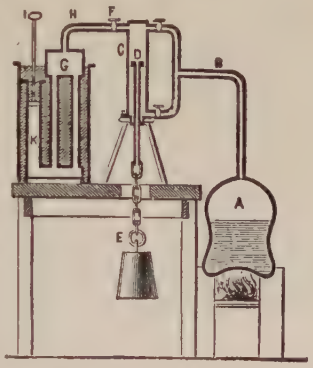


FIG. 118.—Watts experimental condensing chamber.

Watt's work continued rapidly from this point, and in larger models a great number of refinements in design and function were realized. Heat was saved by maintaining the temperature of the cylinder, but further economies in the use of steam were achieved by the discovery of the means of utilizing the expansive power of steam. The atmospheric engine became a steam engine in an accurate sense of the word, and in the process was transformed into

[268] THURSTON, "Steam Engine," p. 89, Fig. 25.

a well-designed machine based upon a sound scientific perception of the outstanding properties of steam. This decisive critical revision in its entirety thus constituted a strategic invention with supplementary inventions and an extraordinary amount of critical analysis. In fact, Newcomen's invention was of greater immediate practical use than is ordinarily the case. In many instances, the strategic invention is wholly useless in its initial form. In the course of technical development the strategic invention becomes progressly less useful, and it is increasingly common to withhold an invention until all the primary critical work has been done.

Watt's concept of the engine quickly carried him beyond the limits of the existing facilities for machine building. Many of the parts presented problems which no existing iron makers were in a position to furnish. The attempt to build a complete engine was postponed even after the patent had been secured Jan. 5, 1769, and when the financial assistance of Dr. Roebuck had been secured the enterprise proved to be beyond his means and he was forced into bankruptcy. In the liquidation of these affairs, Boulton became interested in the engine and finally took over Roebuck's share in the patents in consideration of the adjustment of certain debts. The parts of the engine then being built were moved to Soho in Birmingham (1774) and the new partners proceeded with the enterprise. All attention was at first given to pumping engines which were leased on a royalty basis, but it was difficult to collect the royalties, and demand was small for such engines outside Cornwall where coal was dear. The scale of the enterprise required so considerable a volume of output that Boulton found it essential to develop an engine for general industrial use. Watt thus went to work on the problem of producing rotary motion, and the firm became very deeply committed to this new venture. Patents were taken out in 1781 and 1782 which covered the solution of this problem: the production of rotary motion from the reciprocating motion: the double-acting engine, with steam working alternately on each side of the piston. This last development was essential to the general utility of the engine and must be regarded as the crowning achievement of Watt's career. It proved, likewise, to be the turning point in the activities of the firm, whose prosperity was soon assured.

The gains in the potentialities of the steam engine were not at first utilized to build engines that were more powerful than the atmospheric engines then in use. Particulars are readily accessible

because after 1784 Watt made a practice of rating his engines in the horsepower unit, 33,000 foot-pounds per minute. The rotative engines first made for use in the breweries at London were about 10 horsepower, and after the double-acting engine was brought out a number of 10-horsepower engines were made. The common size was the 20-horsepower engine, though 40- and 50-horsepower units were produced in considerable numbers, and a few 80-horsepower engines.[269]

The increase in the efficiency of the machine is indicated roughly by its cylinder. A double-acting engine with a cylinder of 31½ inches in diameter, with a 7-foot stroke and 17½ strokes per minute was rated at 40 horsepower; rather more than twice the horsepower of an atmospheric engine of similar dimensions. The reductions in the cost of operation are best indicated by the reduction in coal consumption per horsepower. Farey compares performances of 40-horsepower engines. An atmospheric engine by Smeaton consumed 15.87 pounds of coal per horsepower; Watt's engine 8.4 pounds if no use was made of the expansion of steam, 6.26 pounds if an expansion of 1.5 times were secured. Records of Cornish mines indicate a reduction of coal consumption to one-third.

Full exploitation of the new source of power required the development of the high-pressure engine. Economies in the cost of power production could be secured by such means, and practical use of steam for locomotion was dependent upon the reductions in weight and bulk that could be achieved only on this principle. Though closely related to the chain of development that culminated in the perfection of the condensing engine there are some distinctive elements. The conception of the high-pressure engine is nearly contemporary with the earliest achievements in the related field. Papin was on the verge of the discovery of all the essential elements. Leupold sketched a significant model in 1720. A "pressure" engine was invented by Westgarth in 1765 to use a small stream of impure water as a means of pumping pure water from a somewhat lower level. All the valves and piston motions would serve equally well in a double-acting, high-pressure steam engine. Undoubtedly the limiting factor was not the concept, but the practical difficulty of dealing with steam pressures. Neither boilers nor cylinders could then be made that would resist the pressures needed for effective working. The condensing engine

[269] FAREY, "Steam Engine," p. 574.

may be operated through quite a range of pressure, but solicitude for safety made Watt conservative and he refused to accede to Boulton's suggestions to use somewhat higher pressure.

The development of the high-pressure engine was really opened up by the improvements in iron making in the last quarter of the eighteenth century. Projects for an engine of this type were entertained by one of Watt's workmen, Murdock, and a successful model of a high-pressure locomotive engine was made in 1784. Watt used all his influence to dissuade Murdock from proceeding with the project. Meantime, Cugnot in France had made a steam artillery carriage (1770) which was sound in conception, but defective in its proportions. In fact, the problem was essentially critical and practical; many workers were occupied with various schemes and it is not essential to the purpose of the present study to mention the details. Significant achievements were accomplished simultaneously but independently by Oliver Evans in the United States and Richard Trevethick in England (1800–1801). Both were at first concerned with locomotion, but Evans saw little immediate future for a steam locomotive and adapted his engine for use in a mill. Trevethick gave demonstrations of his locomotive at the colliery of Pen-y-darran and subsequently in London. From this time, there was much experimentation with locomotives on the rails already in use in the mining districts, and on the highways. No results were achieved that were of decisive practical importance; it was difficult to raise enough steam to give the engine a significant amount of power, and engineers were curiously slow to perceive the importance of a carefully graded road bed. The self-taught George Stephenson was the first to perceive the crucial importance of grade and curve resistance to the economy of operation of a steam locomotive. This concept lay behind his recommendations for the survey of the Liverpool and Manchester Railway. The initial suggestion of the tubular boiler came from Booth, the secretary of the railway company, but the famous Rocket was built by Robert Stephenson, in consultation with his father and with Booth. The successful demonstrations of the Rocket at the Rainhill tests (1830) marks the completion of the first phase in the development of steam engineering.

Chapter XII

MACHINE TOOLS AND QUANTITY PRODUCTION: 1450–1850

I

Until the close of the eighteenth century, the greater part of industrial machinery was made of wood. Even the water and windmills contained very few metal parts. Instruments of precision, clocks, watches, and much builders' hardware were made of metal and embodied substantial accomplishments in metal working. Firearms of all sizes, and various items of marine equipment were made of metal; brass or iron. The metal trades were by no means unimportant, and the technique of working in metals had made notable advances in the Middle Ages and most especially in the early modern period, but the uses of the metals had not been greatly extended. Production was small. Processes were uncertain and difficult to control. The chemistry of the metallic compounds was not sufficiently understood to emancipate the crafts from the crudest empiricism, and, many attempts at innovation were frustrated by difficulties which we now know to be due to variations in ores and complications arising from small changes in furnace practice.

The last quarter of the eighteenth century is marked by the beginning of a rapid development of methods of refining and working iron, which opened up new uses of iron and steel and soon led to the building of industrial machinery of iron. The new technique of machine building, with some modifications and extensions, also made it possible to produce large quantities of metal wares for general consumption. The highest development of the new technique appears in the system of interchangeable-part manufacture—the manufacture of individual parts within such limits of accuracy that the complete device can be assembled without any significant shaping and fitting. Identical objects had been made earlier, commonly by casting, as in the case of printing type, but as they are not permanently assembled in a definite arrangement they

are not wholly comparable to the individual parts that have become the characteristic feature of modern machinery.

The development of new methods of the production of iron made these new achievements possible: the invention of the steam engine made them immediately essential. Smeaton's comment on the model of the engine is significant. He reported to the Society of Engineers that "neither the tools nor the workmen existed that could manufacture so complex a machine with sufficient precision."[270] At that time Smeaton must inevitably have regarded himself as one of the foremost authorities on machine building. He was then engaged in the manufacture of atmospheric engines, mills, pumps, and other large work. He had developed the compass of the boring machine to produce cylinders for engines and compressed air pumps for blowing iron furnaces. But he was obliged to tolerate errors in his cylinders, amounting to the thickness of the little finger in a cylinder 28 inches in diameter.[271] Watt had an early cylinder with an error of $\frac{3}{8}$ inch. The beginnings of the new development are thus most significantly marked by improvements in the boring machine by Wilkinson (about 1776), which enabled him to deliver adequate cylinders to Boulton and Watt. His achievement made the steam engine immediately practical, though the early engines left much to be desired in accuracy of workmanship despite steady improvement in methods. The great balance beam was thus long retained, because it was not possible to make surfaces accurate enough to enable the engine builder to attach the cross-head to the crank. It was left to Maudslay to make this simplification in the machine after his improvements in machine tools.[272] Each new step forward in tool building thus resulted in practical increases in mechanical efficiency of the whole set of machines.

This rapid conquest of such a new field indicates clearly that the times were ripe for the change, for, in many instances, concepts as brilliant as those of Watt have failed of immediate development in the face of apparently less serious difficulties of application. It is thus especially important to define with some measurable accuracy the conditions which prepared the ground for these truly great achievements in metal working. The final achievement was based upon improvements in the design of certain basic

[270] Roe, p. 2.
[271] *B. G. T. I.*, Vol. XI, p. 120.
[272] Roe, p. 43.

machine tools, the development of rolling mills, heavy forge work, and the casting of malleable iron in wet green sand. Though originally separate accomplishments, the possibility of a new syntheses was perceived towards the close of the eighteenth century. When fully developed this synthesis brought about more far-reaching economic changes than any previous group of technological innovations. As in all such syntheses, the new attainments are more vividly felt as a beginning than as an end, and accordingly it is not without effort that the genesis of this new technique can be recovered and formulated in historical terms.

The most important of the early machine tools were the lathes and boring machines, and of these the lathes were more strikingly developed prior to 1774, though the transformation of the boring machines must be regarded as the first decisive step towards the new technique of working in metals. This is due, of course, to the fact that most of the changes in the design of the lathe were directed towards the enlargement of its compass in the working of wood and the softer metals. The gradation of accomplishment is consequently clearer than in the case of the machines exclusively concerned with metal working.

II

The primitive form of the lathe has already been noted in earlier chapters and, unfortunately, we have little information bearing on the history of the machine in the middle ages. But Leonardo's notebooks contain a few important sketches and thereafter the record is a tolerably continuous. It is difficult, however, to feel much certainty of the precise date of the various innovations in design because the treatises commonly furnish a record of existing practice rather than of innovations by the author. The sketches of Leonardo are so schematic that they are not suitable for reproduction here. They indicate decisively that all the modes of driving the lathe were known to Leonardo. The old bow lathe continued to be used in various forms for light work. The pole lathe, which had presumably been long in use, is first recorded in these sketches. A cord-driven lathe with counterpoised weights is shown and also a lathe driven directly by bands from a wheel. The last two forms of drive, though superior in many ways, were less frequently used than the pole lathe despite the measurable inconvenience of the non-continuous rotation of the

work which limited the action of the tool. In fact, the pole lathe survived far into the nineteenth century, along with the simple bow lathe. Growth proceeded therefore by adding new members to the machines of the lathe family rather than by substitution of new forms for old ones. Each new type of work produced some modifications of the lathe or its attachments.

Although evidence is somewhat scanty, we are probably justified in believing that the dominant type of heavy-duty lathe in

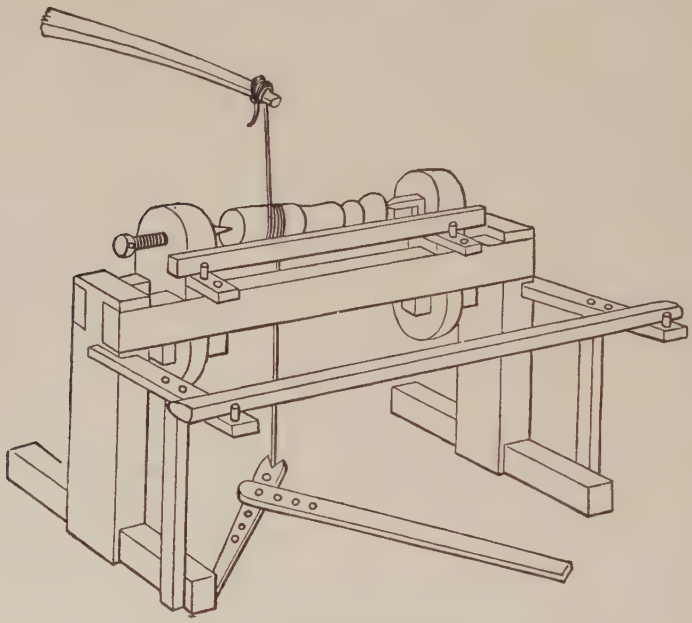


FIG. 119.—Center lathe with pole drive.

Leonardo's time was the plain center lathe with pole drive such as is shown in Fig. 119.[273] The plate is taken from Moxon's treatise of 1677, but earlier sketches, less suitable for reproduction, fix an early date for the introduction of the machine. The pole is fastened to the ceiling so that fully one-half of its length is free. A cord, usually catgut, passes from the free end of the pole around the work and is fastened to a treadle or operated by hand. The work is placed in the lathe between two fixed points, and in its simplest forms, the operative is not really asssisted by tool-holding supports though there is, of necessity, a simple bar

[273] HOLTZAPFFEL, Vol. IV, p. 19, Fig. 20.

upon which the tool is rested. The actual manipulation of the tool rests wholly with the workman.

Some remarkable modifications of the center lathe were made by Jacques Besson, who died about 1568. Drawings of his apparatus were published after his death, but though widely circulated these innovations in lathe design seem to have exerted little general influence. The screw-cutting lathe is shown in Fig. 120.[274] The

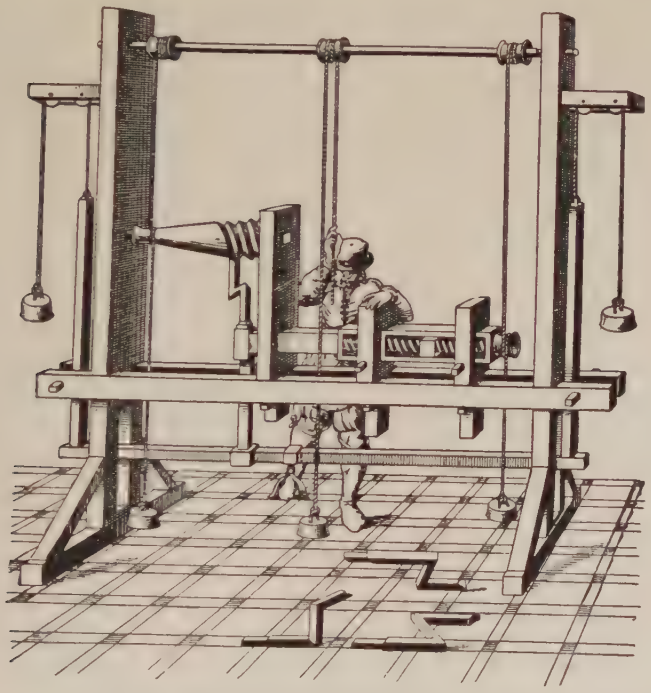


FIG. 120.—Besson's screw cutting lathe.

lathe is driven by a cord passing over a central pulley, the motion being transmitted by other cords to the work and to a lead screw which controls a tool firmly fixed in a support. This crude machine thus contains many of the primary features of slide rest.

"It is, however, worthy of remark, that, bad and imperfect as the constructive arrangement is, this early machine is capable of cutting screws of any pitch, by the use of pulleys of different diameters; and right- and left-hand screws at pleasure, by crossing and uncrossing the cord; and also that in the first machine the

[274] *B. G. T. I.*, Vol. V, p. 101, Fig. 47.

inventor was aware that a screw-cutting lathe might be used upon elliptical, conical, and other solids."[275]

Besson also constructed guides for turning irregular shapes, shown in Fig. 121.[276] A bar containing a guide slot is mounted above the work. By passing a special tool holder through the slot the actual cutting tool can be made to produce a turned shape corresponding to the shape of the slot. The guide bar is further controlled by the circular disks set at an angle to the spindle. The sketch indicates that provision is made for setting these disks at varying angles to the bar by toothed arcs. Properly set, these guides would make the bar 1 rise and fall in slots cut in the frame which cannot be shown in the drawing. A workman could then execute ovals and other irregular shapes. Elements of this apparatus were developed into the rose engine and used by goldsmiths for turning irregular patterns on plate or tracing fine lines in geometrical designs as an ornament. Such work seems to have developed during the seventeenth century, for such applications of the lathe are indicated by drawings of Solomon de Caus (1615), and thorough familiarity with such work is shown by the descriptions of Felibien (1690) and Plumier (1701).

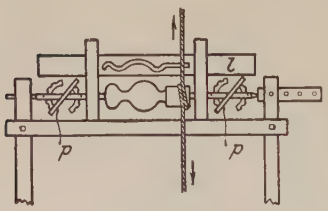


Fig. 121.—Besson's oval turning lathe.

Fig. 122.—Early mandrel lathe, 1568.

The primary development of the lathe in this period centers around the development of the mandrel. By applying the driving power to a spindle attached to the work instead of to the work

[275] Holtzapffel, Vol. II, p. 616.
[276] *B. G. T. I.*, Vol. V, p. 108, Fig. 77.

itself the compass of the lathe was greatly extended. A large class of objects could be fastened to a chuck which could not be turned between centers at all, and it was possible to provide the mandrel with guiding devices which were of great importance prior to the development of sufficient technical proficiency to construct accurate lead screws of considerable length.

The mandrel in its simplest form appears in the wood cut of Hartman Schopper of 1568, shown in Fig. 122.[277] The turner is at work on a sphere which is driven by a live spindle or mandrel. In this case, the mandrel is merely a device for turning the work. With different attachments it would be suitable for turning boxes set upon some sort of chuck. The large development opened up by this device began when iron was substituted for wood in making the mandrel. Plumier in 1701 describes the making of iron mandrels with screw guides cut in them, and the practice of mounting the iron mandrel in metal collars cast of tin or other soft metal began in his time though it underwent considerable development in the course of the eighteenth century. The culmination of this achievement had been reached at the time of the publication of the French encyclopedia in 1785. This late state of the mandrel lathe is shown in Figs. 123 and 124.[278] The frame of the lathe, and the head stocks are of wood, but the mandrel and its fittings are metal. The mandrel assembly may be seen at the left, with the various keys necessary for operating the various guides. The detail of the mandrel is shown in Fig. 124. The metal collars in the wooden headstocks are shaded. These were cast around the mandrel itself, lead or tin being the usual material. The heavy groove at the left end of the mandrel enabled the operator to control the motion; if a master key were wedged into this groove, the mandrel would produce a rotary motion with no traversing motion. If the lathe were to be used for screw cutting, this master key must be depressed, and a guide key wedged into the appropriate guide screw on the mandrel. The mandrel would then traverse and enable the operator to reproduce the screw of the guide. This set of keys may be clearly seen in the general view of the lathe. The compass of the lathe was not limited by the length of the guide on the mandrel, as the operator may shift the position of his tool and thus cut a screw of any desired length. The compass is, however, limited to the number of guides cut on the mandrel.

[277] HOLTZAPFFEL, Vol. IV, p. 17, Fig. 19.
[278] HOLTZAPFFEL, Vol. IV, p. 61, Fig. 63; p. 62, Fig. 64.

"All lathe mandrels mounted in wooden headstocks, however, are more or less subject to change of position from atmospheric

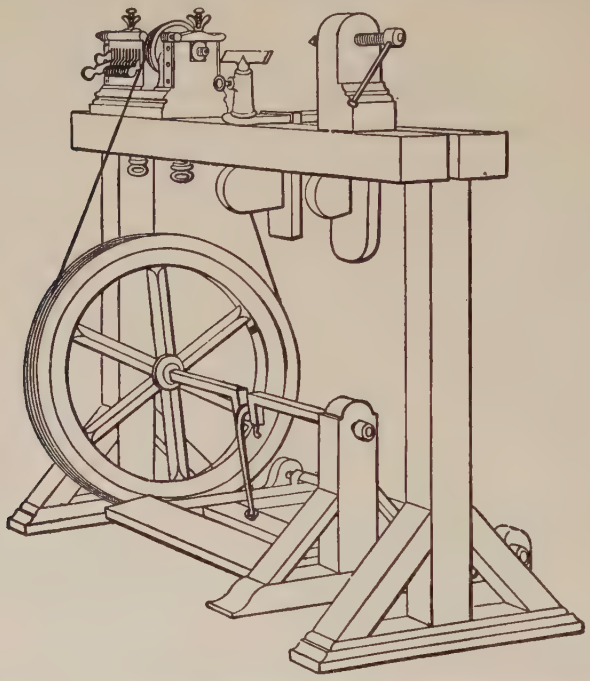


FIG. 123.—Developed mandrel lathe, 1785; general assembly.

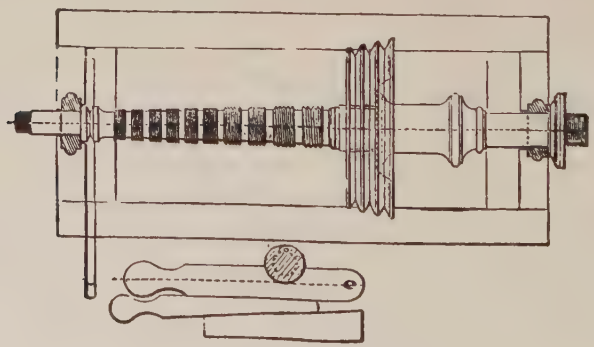


FIG. 124.—Developed mandrel lathe, 1785; detail.

causes, which renders them unsuitable to works of accuracy."[279] Furthermore, the keys and collars are subject to considerable

[279] HOLTZAPFFEL, Vol. IV, p. 65.

wear and the lathe is thus liable to considerable and serious deterioration. The traversing mandrel, however, was the primary reliance of the turner for a full century, and its use restricted the development of the slide rest with a traversing tool to a narrowly limited field. Apart from experimentation with special types of lathes for cutting fusees for clocks and watches, the use of the traversing tool was largely confined to the rose engine of the gold and silversmiths.

The French clock and watch makers of the early eighteenth century are responsible for a considerable development towards instruments of precision. The design of the clock and watch had reached a point that admitted of the achievement of considerable precision, and the importance of the quality of workmanship was keenly appreciated. New apparatus was invented, much of which is described in the treatise of Thiout on clockmaking. The fusee presented one of the more serious problems, because it was a type of screw that was not easily executed with much precision. Thiout devised (1741) a special lathe with a guide screw and traversing tool support which embodies elements of the notion of the slide rest, though no provision is made for holding the tool in more than one position, and some cooperation was required of the workman.

A more notable achievement is embodied in the invention of Le Lievre that was subsequently improved by Gideon Duval. A plate of this machine published by Ferdinand Berthoud in 1763 is shown in Fig. 125.[280] This machine must be ranked as one of the earliest instruments of precision among the machine tools.

"The handle *b* gives rotation to the work; and at the same time, by means of the rack *rr*, and the pinion fixed on its axis, the handle traverses a slide which carries on its upper surface a bar *i*; the latter moves on a center, and may be set at any inclination by the adjusting screw and divisions; it is then fixed by its clamping screws. The slide *s* carries the tool, and the end of this slide rests against the inclined plane *i*, through the intervention of a saddle or swing piece; the slide and tool are drawn to the left hand by the chain which is coiled around the barrel *b*, by means of a spiral spring contained with it.

"Supposing the bar *ii* to stand square or at zero, no motion would be impressed on the tool during its traverse, which we will suppose to require 10 revolutions of the pinion. But if the bar

[280] HOLTZAPFFEL, Vol. II, p. 637, Fig. 610.

were inclined to its utmost extent, so that we may suppose the one end to project exactly 1 inch beyond the other, in reference to the zero line or path of the slide, then during the 10 revolutions of the screw, the tool would traverse 1 inch . . .

"The principle of this machine may be considered faultless; but in action it will depend upon several niceties of construction, particularly the straightness of the slide and the inclined bar . . . " [281]

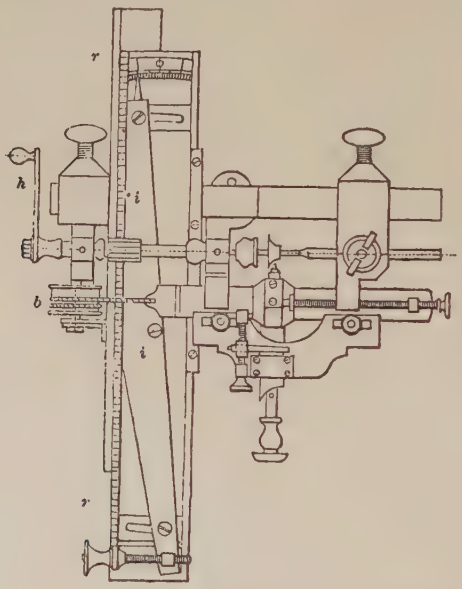


FIG. 125.—Fusel engine, before 1763.

Another mode of preparing accurate original screws developed out of the tangent screw and ratchet which were first applied to the cutting of teeth in clock wheels by Pierre Fardoil (prior to 1741). These features of early French instruments of precision need not occupy us here. The fundamental principles were known; the limitations were largely due to the materials used in lathe construction and to difficulties in execution of the machines even in the combinations of wood and metal then known. Further improvement involved the development of the all-metal lathe.

III

Maudsley's achievements with the lathe are very imperfectly described in the statement that he invented the slide rest. He

[281] HOLTZAPFFEL, Vol. II, p. 638.

made the lathe an instrument of precision capable of working on a large scale by building it entirely of iron and by developing a technique that made it possible to cut accurate lead screws of sufficient length to make it possible largely to abandon the principle of the traversing mandrel for the more flexible principle of the traversing tool.

Maudsley began his active career at the Woolwich Arsenal, in many ways a curious beginning for one whose distinction lay in the high standards of accuracy that he set for his work in metals, though it is not so strange when one realizes that at that time the chief and ultimate instrument of precision in the heavy metal trades was the file. One of his old workmen said:

"It was pleasing to see him handle a tool of any kind, but he was quite splendid with an 18-inch file." His great opportunity came when Joseph Bramah, by trade a cabinet maker, was casting about (1789) to find some workmen to assist in the production of a newly patented (1784) lock. Maudslay was recommended to him and accepted despite his youth. The locks created a new problem. Their design required higher standards of accuracy than were then commonly achieved in the metal trades, and yet it was proposed to manufacture them in large numbers. It was, therefore, necessary to secure high standards of workmanship without sacrificing volume of production. We know little of the detail of the development of the early lathe and the lock-making apparatus, but it is generally held that the all-metal bar lathe set up in Bramah's shop (1794) was largely if not exclusively the work of Maudslay. The head and tail stocks and the slide rest were carried by a triangular bar mounted on castings. The surfaces of the bar were prepared by chisel and file; the triangular form being chosen to simplify the task of surfacing, as in such a form it was necessary to finish only two surfaces. The design of the slide rest was highly original, but it proved to be unsatisfactory in a number of respects so that substantial modifications were made by 1797. In general, the primary features of the French slide rests were adopted in this and later lathes.[282]

Although most English writers and some Americans place the primary stress upon the use of the slide rest with a traversing tool, the German writers and some others attach more significance to the fact that the new lathe was made wholly of metal. The

[282] *B. G. T. I.*, Vol. V, p. 102–104; Vol. XI, p. 124; HOLTZAPFFEL, Vol. IV, pp. 66–67.

ultimate adoption of the primary features of the tool support of the French rose engine indicates clearly that the support was not original either in general concept or detail of design. Only a faulty concept of the nature of the process of invention could create so much confusion in the description of the actual accomplishment. At so late a state in the total process of achievement, the conceptual or saltatory elements had become subordinate in importance to critical revision in execution and construction. The manufacture of the new lock had redefined the entire problem of turning in metals by placing primary emphasis upon the attainment of accuracy without prohibitive cost. The perception that

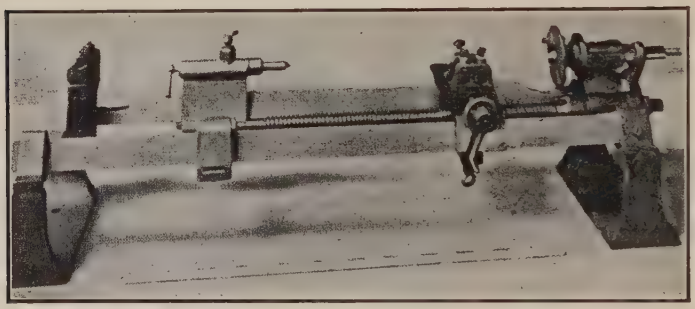


FIG. 126.—Maudsley's improved bar lathe, with slide rest.

metal was the proper material for construction was of commanding importance, and the competent execution of the lathe in iron was a truly epoch-making achievement. All the individual elements were old, but the medium and the synthesis were distinctively new. At about the time of the revision in the design of the lathe (1797) Maudsley left Bramah and set up a blacksmith and jobbing shop on his own account. Under these new auspices his work was carried into new fields. A small screw-cutting lathe was developed prior to 1800, which embodied many substantial improvements in methods of screw cutting. The improved slide rest of 1797 is shown in Fig. 126.[283] Neither this lathe nor the original screw-cutting lathe was designed to be driven by steam or water power. The general-duty lathe was long turned by a cord from a great wheel turned by cranks. The early screw-cutting lathe was turned by the operator. There was no obstacle to the substitution of other

[283] ROE, plate facing p. 42.

forms of power as soon as the compass of the lathe could be increased sufficiently to require such power.

The distinctive feature of the screw-cutting lathe is the provision of various combinations of geared wheels to enable the operator to produce screws of any desired pitch without change in the lead screw. This concept appeared explicitly in some of Leonardo's screw-cutting mechanism and implicitly in the various pulleys of Besson's screw-cutting lathe, but in the intervening period other methods had commanded attention and such modes of varying screws dropped out of sight. Apparently, this use of geared wheels was a possibility well within the range of general mechanical knowledge though the difficulty of making adequate lead screws had given the primacy to the traversing mandrel for the major part of the eighteenth century.

The lathe of 1800, however, was the beginning rather than the end of Maudsley's work on the screw. In the course of the next 10 years he made exhaustive studies of the problems of screw-cutting and succeeded in placing this fundamental aspect of metal working upon a solid foundation. The production of accurate lead screws of great length and substantial diameter was essential to the increase in the compass of the newly designed lathe. Every resource was exhausted in the development of accurate original screws. Beginning with the best of the hand methods, numbers of screws were prepared and the best of them selected for further work in specially constructed lathes. "A very excellent brass screw about 7 feet long" was finally constructed "which was less than one-sixteenth of an inch false of its nominal length." A device was then constructed to remedy this error and the new screw produced was examined with micrometric apparatus, together with a screw prepared by Mr. Barton a friend of Maudslay, who had been working along different lines. It then appeared that both screws contained many irregularities, being unequally coarse in parts, and irregular in their angles. Both screws were then subjected to further corrections until they became accurate within any margins of error then significant for mechanical or even scientific purposes. Holtzapffel concludes:

"I believe it may be fairly advanced, that during the period 1800–1810, Mr. Maudsley effected nearly the entire change from the old, imperfect, and accidental practice of screw making . . . to the modern, exact, and scientific mode now generally followed by engineers; and he pursued the subject of the screw with more

or less ardour, and at an enormous expense until his death in 1835."[284]

These accomplishments with screws were the basis of the later achievements of Maudsley in building heavy machinery and were in a large measure the basis for the development of the machine tools themselves. From this point the increase in the compass of this family of tools was rapid. Lathes for copying irregular shapes were developed by Bentham, Brunel, and Blanchard. Planers and milling machines soon followed, so that by 1840 most of the primary machine tools in this group had assumed stabilized forms.

The boring machine is of great antiquity in the wood-working crafts, as pump barrels were made by boring solid trunks of wood, from an early date; but applications to the metal trades were slow. The chief task was boring cannon of bronze or cast iron. Leonardo devised apparatus for metal working similar in general features to the machines used on wood. A horizontal boring rod driven by water power or a tread wheel was driven against the work, which was mounted on a moveable carriage and drawn forward by a winch turned by the workmen. Leonardo sketched apparatus of this type, and a more complete drawing is to be found in Biringuccio's "Pirotecknika" (1540). Biringuccio's drawing is shown in Fig. 127.[285] These early machines were not designed to bore a solid piece but only to finish a casting already hollow.

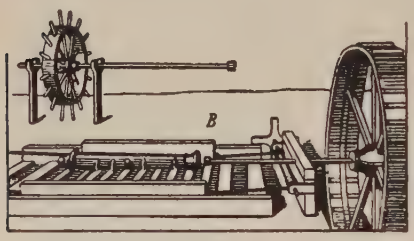


Fig. 127.—Biringuccio's boring engine.

In the seventeenth century, most of the cannon-boring engines were vertical, as is shown in Fig. 128.[286] The cannon is suspended over the drill and held against it by gravity. In this case the drill is turned by a horse gin adapted to the use of two horses. Beginning in 1713, a Swiss, Maritz, introduced improvements in the horizontal drill (1713), and was able to bore cannon from solid castings by some form of center drill so that the core was removed in a single piece. This device was introduced by its inventor in

[284] Holtzapffel, Vol. II, pp. 641–647.
[285] *B. G. T. I.*, Vol. XVII, p. 117, Fig. 1.
[286] Beck, G. d. E., Vol. III, p. 602, Fig. 166.

Spain and France, and engines of similar general form were applide in England and Sweden.[287]

The introduction of the Newcomen engine created new and difficult problems for the iron masters which were solved only incompletely. The early cylinders were finished by grinding and filing, but the process was costly. The large diameter of the

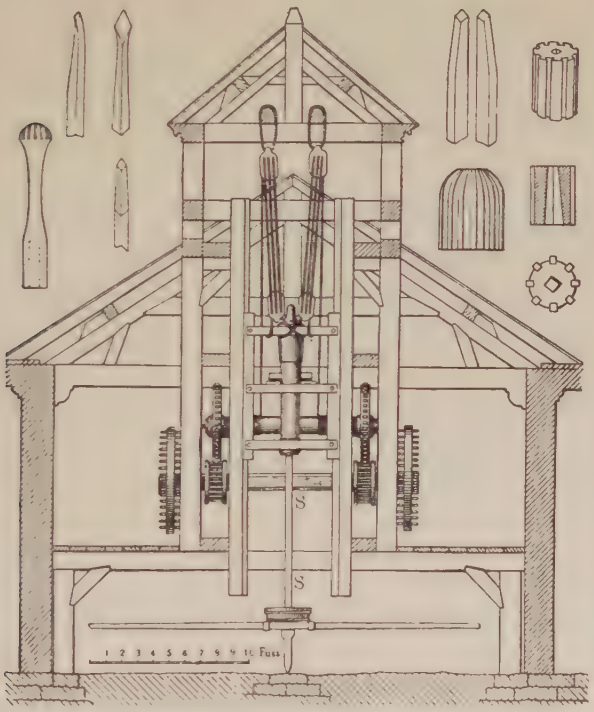


FIG. 128.—Vertical boring engine, eighteenth century.

cylinders was the source of most of the embarrassment: for diameters of 30 to 60 inches necessitated such heavy drill heads that the tools worked effectively on only a portion of the cylinder at a time. Attempts were made to take four cuts of 90 degrees each, but results were uncertain and unsatisfactory. Smeaton endeavored to overcome these difficulties by supporting the drill head upon a small carriage running in the cylinder, but this merely reproduced the irregularities in the original casting and there was

[287] BECK, G. D. E., Vol. III, pp. 602–603.

no certainty that the inside of the cylinder would be straight and true.

The first notable improvement was made by John Wilkinson, and is embodied in the patent of Jan. 27, 1774, for a method of boring cannon from solid castings. The drill was set up on a strong bench, having only a forward motion derived from a rack and pinion. The cannon was mounted on heavy wooden collars and attached to a spindle driven by water or steam power. The casting was bored to a suitable calibre by the successive application of a series of drills.[288] The tool and the work were thus sustained independently of each other and the accuracy of the work correspondingly improved.

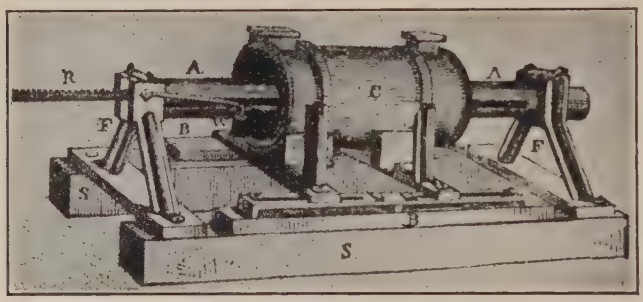


FIG. 129.—Wilkinson's boring engine.

Within two years Wilkinson began to finish cylinders and condensers for Boulton and Watt of a degree of accuracy significantly beyond any previous achievement. The process by which these results were obtained is unfortunately not known. At a later date, he was using a boring engine in which the cylinder was securely fixed on blocks, whereas the drill head was carried on a heavy rod which ran through the cylinder and was sustained at both ends. The drill was carried forward through the work by a rack and pinion contained within it. The general character of this apparatus is shown in Fig. 129.[289] The earliest dated drawing of this engine is a sketch of 1795 recently discovered among Watt's papers.[290] This machine was only one of many important contributions to the heavy-metal trades. In 1777, Wilkinson applied

[288] *B. G. T. I.*, Vol. III, pp. 222–223.

[289] ROE, p. 14, Fig. 7.

[290] FORWARD, E. A., "The Early History of the Cylinder-boring Machine," *The Engineer*, Vol. 138, pp. 686–715, 1924; *B. G. T. I.*, Vol. XVII, p. 118.

the steam engine to raising a stamp hammer of 60 pounds, and in 1783 a forge hammer had been constructed weighing 7.5 tons. Wilkinson was thus able to handle large forgings at an early date and though Naysmith made signal improvements in the design and control of the steam hammer the primary change in the compass of iron forging must be credited to Wilkinson. His rolling mills, coining presses, drawing benches, and cupola furnace were all improvements of first-class importance and the list of his inventions is by no means exhausted by this enumeration. By a strange caprice of public fancy, this grim and unattractive character has never secured the fame that he deserves as one of the pioneers in the development of the heavy-metal trades.

Although the general development of a metal using technique was necessarily dependent upon the mechanical accomplishments just described, a precedent condition of commanding importance is to be found in the rise of the modern technique of iron founding. The foundry supplied the unfinished shapes for a large part of iron machinery and all the basic castings for frames and supports that could be used just as they come from the founders' hands. While, therefore, the final achievement of iron machinery was postponed until the primary machine tools had been developed, the possibility would never have been presented had not foundry practice already been perfected.

The rise of iron founding involves a number of striking innovations, whose magnitude and difficulty is not apparent until these processes are considered in some little detail. Iron castings began to be made in the late medieval period, after a technique largely taken over from the brass founders. The most general procedure was based upon the use of a mould prepared with loam. The properties of the medium required a painstaking preparation of a mould that was dried and finished with great care. The process was costly, but by no means ill-adapted to the production of expensive articles of art or luxury in bronze. Iron objects for general consumption, however, could not be sold at a price that was compatible with such costs. Furthermore, there were metallurgical difficulties. Early iron casting had been based on the use of molten cast iron taken direct from the bloomery furnace. But despite some heat economy, such a practice was incompatible with the development of any extensive industrial use of cast iron, because of the wide variations in the quality of cast iron. The physical properties of cast iron vary through a wide range on account of

differences in the form of the carbon and the amounts of silicon. When a considerable proportion of the carbon is precipitated in crystals of graphite the iron is relatively soft and eminently suited to use for general industrial castings. Such pig irons are classed as grey iron, several grades being commonly recognized. When the carbon exists largely in combined form, the iron is white and of close texture, brittle, and weak. The development of iron founding thus required much grading of the crude pig and commonly reheating and refining to secure an adequately standardized product. Before the development of analytical chemistry, all this metallurgical work was highly empirical. The problems were not understood and only a painful experience could furnish any guide. At the begining of the eighteenth century none of these properties of cast iron were known and there were no refining furnaces adequate to the refining of foundry iron in significant quantities. The decisive work in this field was done by Reaumur and the Darbys; working in complete independence. Reaumur was a scientist, to whom these problems were a matter for experimental research. The importance of the results were clearly recognized by him, but no attempt was made to commercialize processes developed. Abraham Darby was a practical iron master concerned first and foremost with the production of iron hollow ware on a commercial basis. The work of the two men is complementary, as Darby gave his primary attention to the technique of casting in wet sand, whereas Reaumur was primarily interested in refining pig iron and determining its qualities.

Darby was planning to introduce into England the continental technique of casting kitchenware in loam. He went himself to Holland to learn the process, and brought back some skilled workmen, but all their castings were imperfect. Darby was then urged by a helper to attempt casting in wet sand. Adequate results were obtained and in 1708 a patent was secured. With this process, the castings could be made more rapidly, and their weight considerably reduced. The general introduction of the process is undoubtedly the work of Darby, but Reaumur seems to have known of the process, and as he could scarcely have had any knowledge of Darby's work, there is ground to suppose that the process was not wholly unknown in Europe.

Reaumur in experiments published in 1721 shows a substantial appreciation of most of the metallurgical problems involved. By microscopic examination of various cast irons, he was able to

recognize all the primary classes: in all 10 grades are given, which seem to correspond roughly to many of the grades now recognized. He appreciated the importance of grey iron for foundry work and recognized the tendency of grey iron to become white with reheating. Attempts to convert white iron into grey iron failed, and the technique was developed upon a basis of selection of the proper grades of pig iron for foundry work and treatment was designed to change their properties as little as possible. Reaumur's process was neglected in France for many years, but iron founding was substantially developed by the middle of the century. In England the humble field of kitchenware was rapidly extended and to these demands new requirements were added by the development of the Newcomen engine and the demands for heavy artillery. The technique was thus fully established before the more familiar industrial demands arose at the close of the century.

IV

The developing technique of the metal trades opened up new possibilities in quantity production and in the manufacture of interchangeable-part mechanism. These two processes are closely related, but some distinction is desirable. Interchangeable parts must be assembled in a stable and permanent relationship. The production of interchangeable parts obviously requires a greater degree of precision in manufacture. Quantity production of relatively identical units begins, therefore, in a strict sense with the development of the casting of moveable types, though this trade was so long an isolated case that it does not commonly enter into our thinking. Further developments in the small-metal trades followed. Of great significance was the increased proficiency in die stamping embodied in the improved technique of coinage introduced in the sixteenth century, though there were no notable extensions of these methods for a long time. In 1680 a special stamping machine was devised in Nuremberg for fixing heads on pins. The general arrangement is shown in Fig. 130.[291] The frame of the machine was made of wood, but the anvil *v* and the die *z* were of metal. Anvil and die were cut to represent one-half of the pin head, and they must needs register accurately. The die was heavily weighted with lead so that it fell by its own weight, being lifted for each stroke by the pedal worked by the operator. Most

[291] Beck, G. d. E., Vol. III, p. 267, Fig. 43.

of the other processes of pin making were hand work, but there was considerable specialization of work. Early in the eighteenth century the industry had thus achieved that high degree of division of labor made famous by Adam Smith's description.

The most notable early development of quantity production is the manufacturing establishment planned and directed by Christopher Polhem at Stiernsund, Sweden. Polhem, or Polhammer, (1661–1751) was a distinguished scientist and engineer whose plans were a direct result of substantial practical experience and keen realization of all the economic advantages to be achieved

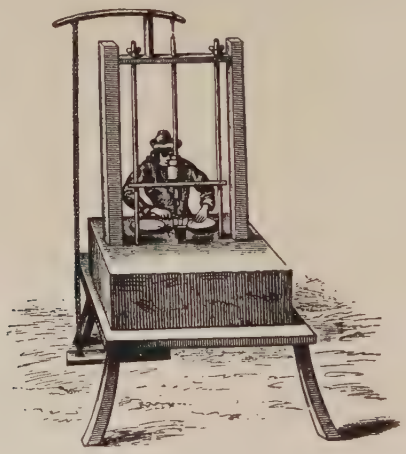


FIG. 130.—Stamping machine for forming pin heads.

by a general application of mechanism to industry with an elaborate division of labor. He says:

"Gain may be secured in all things but most especially in industrial installations by saving labor so that the products need not be so costly, for nothing increases demand so much as low prices; therefore, there is great need of machines and appliances which will, in one way or another, diminish the amount or intensity of heavy manual work. This result can be most adequately achieved by the substitution of water power for hand work with gains of 100 or even 1,000 per cent in relative costs."[292]

With these ends in view a manufacture of various metal objects was established at Stiernsund about 1700, employing about 100 men. Water power was applied to all possible stages in the

[292] BECK, G. D. E., Vol. III, p. 243.

manufacture of household apparatus, tools, and articles of iron. Plough shares, harrow teeth, and hammer heads were among the coarser articles made; gun locks, door locks, clock wheels, tin plates and vessels were among the lighter and more elaborate shapes. When it was not possible to apply power to all stages of the process, intermediate shapes were made by power machinery, to be finished by smiths each of whom was confined to the performance of a single operation. Much special machinery was invented;

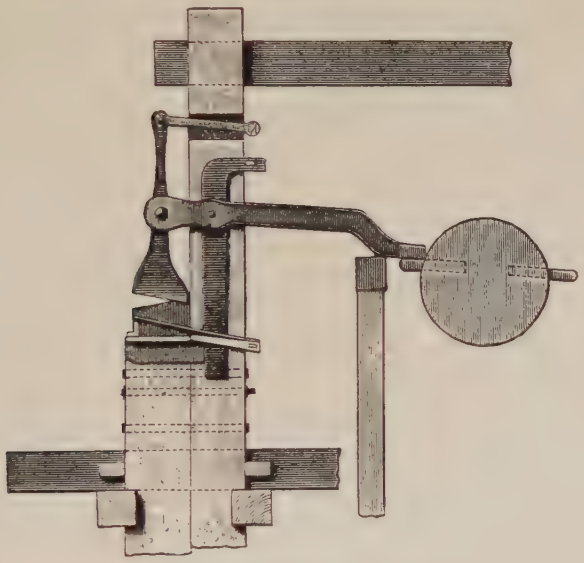


FIG. 131.—Polhem's nail shears.

notably a machine for cutting teeth in wheels for domestic and tower clocks, for hammering pans and plates out of tin-plated iron sheets, for shaping deep cups and vessels out of tin plate, a slitting mill for nail making, a shearing mill for cutting bars, shears for cutting metal roof tiles, a large press for pressing roof tile, heavy rolls for sheet and band iron, power machinery for polishing rolls for the rolling mill.

The shearing engines and the rolls were of permanent significance. The profile of one of the shearing engines is shown in Fig. 131.[293] The general frame is obviously made of wood, but many parts are made of metal, including the lever arm. From

[293] BECK, G. D. E., Vol. III, p. 600, Fig. 165: See also, *B. G. T. I.*, Vol. V, p. 341, Fig. 29.

Stiernsund the power-driven shears spread to the rest of Sweden and ultimately to other countries. They became the basis of considerable increases in the export from Sweden of finished and partly finished nails. The use made by Polhem of the rolling mill is also noteworthy, for continental developments of rolling mills have received scant attention from English writers and many suppose that the early use of rolls for working iron and other metals was confined to the lightest possible uses. Leonardo da Vinci's notebooks show unmistakable sketches of rolls for very light duty, and it is therefore difficult to suppose that there was no knowledge of the rolling mill prior to the English patents of the early eighteenth century. Polhem was clearly using rolls on a considerable scale for the smaller merchant bars, plates, and sheets. Polhem's largest rolls were 10 inches in diameter, which were not much smaller than English rolls at the close of the century. This process of metal working, however, did not strike root on the continent and found its large development only in England where it was first introduced in the tin-plate industry and subsequently transferred to the iron trade.[294] Unfortunately, we have little information in regard to the contacts between the English metal workers and Sweden, though there was enough scientific travel to make complete independence of development unlikely.

This manufacturing establishment at Stiernsund was somewhat incidental to Polhem's work on mining machinery and to his scientific work. He was engaged in much significant experimentation upon mechanical subjects and founded an industrial museum which included models of noteworthy machines seen by him during his travels as well as models of many of his own inventions and scientific apparatus. His career is of undoubted importance in the history of science and technology, but it is of especial importance in any study of the relation of invention to economic development; though a man of commanding talent his name is little known because his best work was far in advance of his time and his environment gave him only the water wheels and clumsy wooden machines that were soon to be supplanted by steam and iron.

Though the advantages of quantity production with special power machinery were thus clearly perceived at an early date, the applications were confined to very narrow fields until the beginning of the nineteenth century, when the influence of a more sophisticated technique in machine building made itself felt. In the

[294] Beck, G. d. E., Vol. III, pp. 579–598.

field of woodworking notable results were achieved by Brunel and Bentham in the manufacture of blocks for the navy. The scheme was conceived independently by the two men, but they were brought together at an early date and they worked together in perfecting the plans for the manufacture, under contract to supply all the requirements of the royal navy. The complete outfit of machinery embraced 44 machines.

" . . . divided into four general classes. First, sawing machines, both reciprocating and circular, for roughing out the blocks. Second, boring, mortising, shaping, and "scoring" machines for finishing the blocks. Third, machines for turning and boring the sheaves, for riveting the brass liner and finish facing the sides . . . Fourth, the iron pins on which the sheaves turned were hand forged in dies, turned and polished."[295]

The machines were built by Maudsley, so that the enterprise represents likewise the beginnings of specialized engineering work in which the contracting firm executes plans furnished by the inventors.

"These machines were thoroughly modern in their conception and constituted a complete range of tools, each performing its part in a definite set of operations. By this machinery 10 unskilled men did the work of 110 skilled workmen. When the plant was in full running order in 1808 the output was over 130,000 blocks per year, with a value of over £250,000, an output greater than that previously supplied by the six largest dock yards."[296]

Brunel devised other wood-working machines but they were not financially successful, and the example set by the block manufacture was without immediate consequence in England.

The slightly more refined system of interchangeable-part manufacture appears in England and on the continent towards the close of the eighteenth century. At some date shortly before 1785, a Frenchman named Le Blanc began the manufacture of muskets upon this principle. The little that is known of the scheme is embodied in Jefferson's letters, the first of them from Paris under date of Aug. 30, 1785. The plan had been approved by the government and at that time the machinery had been developed sufficiently to furnish the complete lock, though all the work on the barrels and stocks remained to be done. Much intrigued, Jefferson had visited the workman.

[295] Roe, p. 29.
[296] Roe, p. 31.

"He presented me the parts of 50 locks taken to pieces, and arranged in compartments, I put several together myself, taking pieces at hazard as they came to hand, and they fitted in the most perfect manner."[297]

Later correspondence states that the project was carried through to the manufacture of barrels and stocks on the same principle. Jefferson endeavored to have the United States bring the man over, but the attempt failed through indifference here. A similar scheme was partially carried through by Bodmer at St. Blaise in the Black Forest about 1806. The full establishment of the technique, however, is due to the work of Eli Whitney, Simeon North, Eli Terry, Chauncey Jerome, and Samuel Colt. The work initiated by these men not only came to dominate the manufacture of fire-arms and clocks but was extended by them and their workmen to a large field of other machinery and apparatus. Priorities have been acrimoniously debated between adherents of Whitney and North, but the claims of North have been overstated by members of his family, and though he made notable contributions to the machinery set up at the Harper's Ferry arsenal his work was certainly not prior to that of Whitney, nor of such broad range in its underlying concepts.

Failure to realize large gains from the cotton gin, because of the difficulty of enforcing his patent rights, required Whitney to develop some gainful occupation. He outlined his scheme to the Secretary of the Treasury in a letter early in 1798:

"I should like to undertake the manufacture of ten to fifteen thousand stand of arms. I am persuaded that machinery moved by water, adapted to this business would greatly diminish the labor and greatly facilitate the manufacture of this article. Machines for forging, rolling, floating, boring, grinding, polishing, etc. may all be made use of to advantage."[298]

A contract was concluded and a mill built at Whitneyville, Connecticut. The mill, employing about 60 men, was not put into operation until 1800. Then, or shortly after he was able to demonstrate his accomplishments to the Secretary of War by assembling 10 muskets from parts selected at hazard from separate piles of parts. Ordnance officers of France and England had declared the scheme impossible and officials in Washington were not without skepticism. North had begun making pistols by

[297] Roe, p. 130.
[298] Roe, p. 132.

somewhat similar means about 1800, and further contracts were secured by both men. The government introduced the system of interchangeable-part manufacture in both the Springfield and the Harper's Ferry arsenals, after the official adoption of Hall's patent gun in 1819. Whitney and North assisted in the installations of machinery.

Although the general concept of this system of manufacture was achieved at an early date, the process itself underwent considerable development over a long period. Much of the earliest work still required hand filing, though the workmen were guided by jigs so that the parts turned out were closely similar. Hand work was at first required on the musket stocks. The complete mechanization of the process involved the full development of drop forging, die stamping, and pattern turning; the primary accomplishments being achieved by 1830–1835. Some progress had been made in all these fields prior to the American work, but the American contributions were considerable in each of these branches of machine tool construction. The Americans also contributed the milling machine to the group of machine tools, anticipating by a few years, English development in that respect. No adequate description of these accomplishments, however, is possible without going far beyond the limits of the present sketch.

These methods were developed somewhat independently in the clock trade by Terry and Jerome. Terry began to realize economies by making wooden clocks in large lots, and when brass was substituted for wood in the wheel work, it became possible to prepare the wheels expeditiously and accurately by stamping them with dies from sheets of brass. It was these methods of production that resulted in the great reductions in price which characterized the early history of clock making in Connecticut. The final establishment of the new technique was marked by Chauncey Jerome's decision (1830) to manufacture 1-day clocks by these methods.

The technique of interchangeable-part manufacture was thus established in general outline before the invention of the sewing machine or the harvesting machinery. The new technique was a fundamental condition of the great achievements realized by inventors and manufacturers in those fields. It made it possible to place the sewing machine in the home and it generalized the use of the harvesting machinery of McCormick and Deere with astonishing rapidity. American engineering and manufacturing

firms took the lead in this general development, achieving distinctive results over an important field that was steadily enlarged decade after decade. The group of machine tools became more and more automatic, and it became possible to build highly specialized machinery for manufacturing firms. Great refinements of execution were achieved with the simplest labor of attendance. These highly developed machine tools are the most distinguished "iron men" of the modern industrial world, for they make possible that substitution of machinery for labor that is so happily described as affecting a "transfer of skill."

Chapter XIII

THE PRODUCTION AND DISTRIBUTION OF POWER SINCE 1832

I

The development of the atmospheric and steam engines furnished a basis for the generalization of the use of power in industry. The serious limitations of water wheels were overcome both in respect of the amount of power that could be economically produced in a single unit and as regards its location. Substantial power could be produced with steam in any location in which sufficient fuel was available, so that supplies of coal were given a new economic importance. But these new prime movers were subject to some sensible limitations in size and the new emphasis upon coal placed many old industrial regions at a serious disadvantage. There was thus a new need for the development of hydraulic motors, for important water powers were available in many of the regions least adequately supplied with coal. Persistent attempts had been made to utilize water powers more completely for a long period of time, but these efforts were not successful in any appreciable measure until the perfection of the turbine water wheel by Fourneyron in 1832. Until then, water wheels were of the two primary types horizontal and vertical, introduced at the beginning of the Christian era; and, though the overshot wheel had been developed, its superiority was not clearly appreciated until the middle or the end of the eighteenth century. The invention of the turbine opened up potentialities that are even now incompletely exploited, for wheels constructed on this new principle could be designed to utilize the full head of the greatest water falls, and relatively small volumes of water would produce large amounts of power. All significant limitations of the amount of power procurable were overcome soon after the invention was brought out. A 50-horsepower wheel was built by Fourneyron at the time his original patent was taken out, and shortly before 1855 an 800-horsepower turbine was installed in the Parisian water

works at the Pont Neuf. With the development of the technique of long-distance transmission of electricity, hydraulic power could be distributed over large areas and at once became the cheapest source of power. When heat energy is not required, hydroelectric power can thus compete with coal as a source of power on more than even terms, and for many purposes even heat energy can be produced in commercially important quantities without excessive cost. This development of water powers, therefore, exerts an important influence upon the regional distribution of industries and makes it possible for regions without mineral fuel to develop power-using industries on a large scale. The invention of the turbine was thus an achievement of the first magnitude in respect of the generalization of the use of power and it is no mere extravagance of national pride that led the noted French engineer Poncelet to compare Fourneyron's contribution to that of Watt.

The name "turbine," first used by Burdin in 1824–1825, is felicitously applied to these new water wheels, because they should be sharply distinguished from the older types of water wheel. In the older types, whether dominated by the weight of falling water (overshot) or by the impact of a rapidly flowing stream (undershot), there was no motion of the water *relatively to the buckets or floats of the wheel.* In the turbine, the flow of the water through pipes, or ducts, or over curved vanes is essential to the operation of the motor. The power is derived from the impulses and reactions set up between the fast-flowing water and the curved passages within which it is contained. As these effects cannot be secured unless the water is confined, the water in the wheel must be contained in tubes or confined to channels established between the vanes and some external and closely fitting casing. The sketch by Leonardo reproduced in Fig. 132, [299] shows the beginnings of the transition from the old Greek or Norse water wheel to the turbine. There are curved vanes to be acted upon by a stream directed against them by a conduit. If we may assume that the plate in Belidor is merely a more complete representation of the same wheel,[300] the wheel is raised above the level of the tail-racewater so that it operates as a turbine with

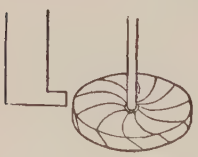


Fig. 132.—Horizontal impulse wheel, Leonardo da Vinci.

[299] Beck, G. M. B., p. 109, Fig. 124.

[300] Belidor, Vol. I, 1. Book 2, Chap. 1, p. 38, Plate 4.

partial admission, without a casing. With a casing, it would be similar in general design to the "tangent" wheel brought out by Zuppinger in 1850. The wheel as described by Belidor in 1737 was in general use in southern France and in Italy.[301]

A closer approach to the turbine is to be found in the pit or tub wheel, of which the earliest drawing now known appears in Besson's sketches (1568). The general arrangement is shown in Fig. 133.[302] A cone-shaped rotor is placed in a pit of masonry. The water enters at the top at a tangent to vanes fastened on the cone. It acts upon them both by impact and by weight, but as the adjustments were not close, a considerable quantity of water escaped between the sides of the pit and the vanes. By the beginning of the eighteenth century the adjustments began to be improved and this motor began to achieve more and more of the distinctive economies of the turbine. The wheel was widely used in Southern France on the Garonne.

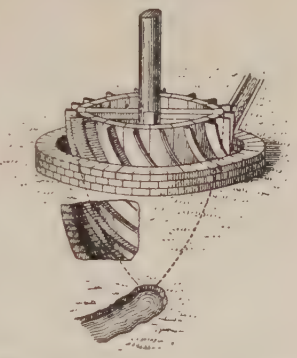


Fig. 133.—Tub, or pit wheel, Besson.

At Toulouse a water wheel was built early in the eighteenth century which embodies even more completely the essential features of a turbine. The general features of the installation are shown in Figs. 134, 135, and 136.[303] The water of the river was led between piers of masonry into sluice ways (7 in Fig. 134). At the end of these sluices horizontal wheels were set designed as shown in Fig. 135. It will be noted that the vanes of the old horizontal wheel have been considerably transformed and that their ends are united by a casing. The wheel was completely submerged. Like the tub wheel, it failed of achieving all the turbine effects, because some water escaped to the tail race without passing through the wheel, as there was considerable clearance between the edge of the wheel and the chamber in which it revolved. These last two types of wheel were the horizontal wheels to which

[301] All the early turbines are described in Crozet-Fourneyron, "*L'invention de la turbine.*"

[302] Beck, G. M. B., p. 195, Fig. 216; Belidor, Vol. I, 1, Book 2, Chap. I, p. 38, Plate 1, Fig. 5.

[303] Belidor, Vol. I, 1, Book 2, Chap. I, Plate V, Figs. 1, 4, 5.

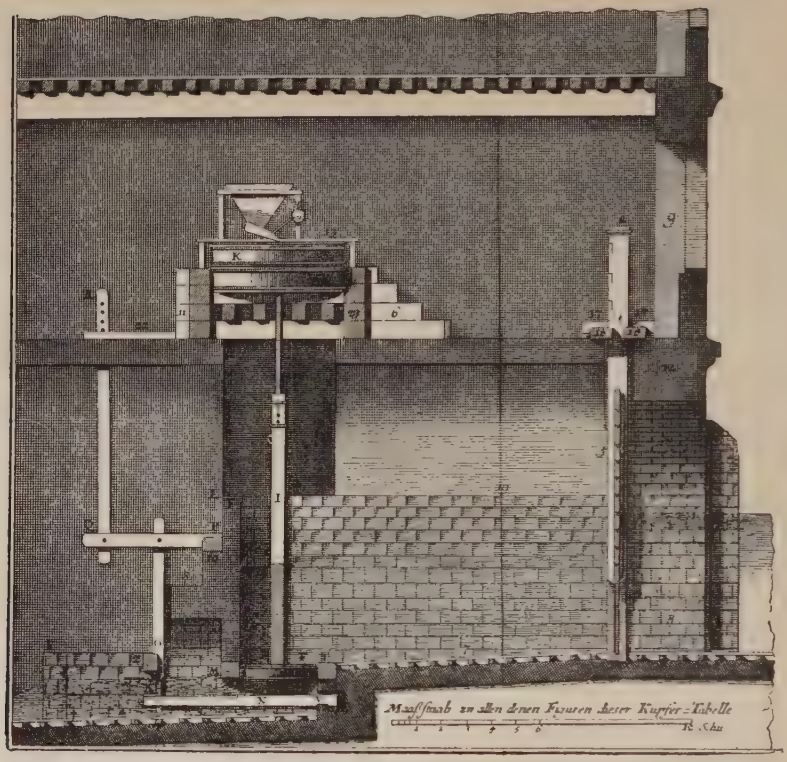
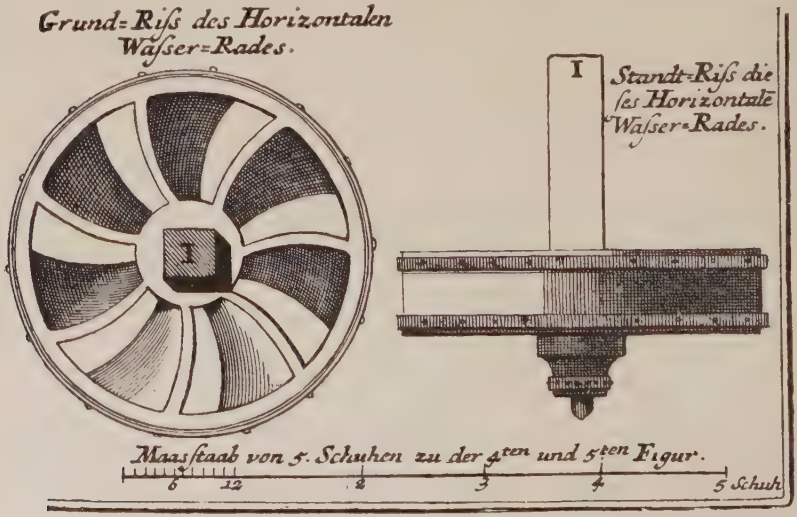


FIG. 134.—Early turbine at Toulouse; about 1700. General assembly.



FIGS. 135 and 136.—Early turbines at Toulouse, detail.

the Society for the Encouragement of Industry referred when a prize was announced in 1823 for the improvement of the hydraulic turbines of Belidor. The developed turbine is thus the result of a critical revision of various horizontal water wheels which became common in Southern Europe in the fifteenth and sixteenth centuries. This final stage of work on the water wheel was based upon the development of knowledge of hydraulics during the

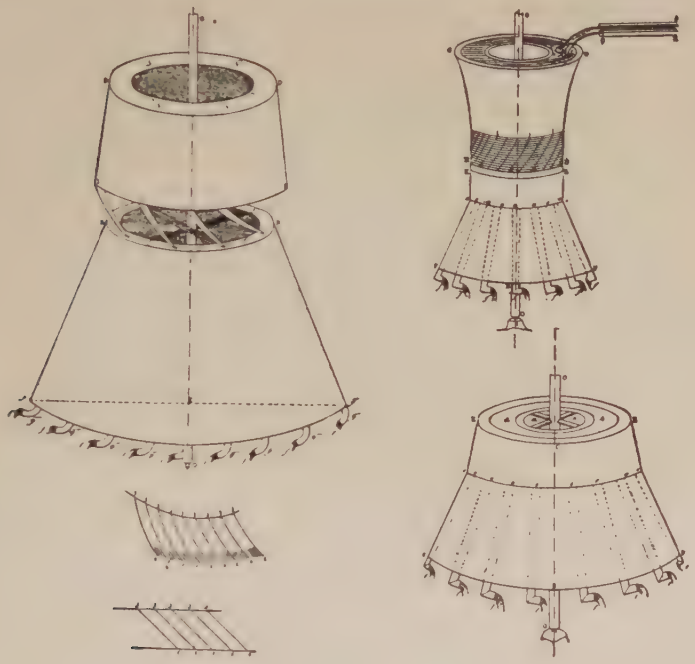


FIG. 137.—Euler's reaction turbine, 1750–1754.

eighteenth century as result of the fuller application of mathematics and experimental methods.

The first experiments to determine the efficiency of water wheels were made by Christopher Polhem early in the century. By the middle of the century, study of hydraulic principles was well launched. Important work was done by Euler (1750–1754), Defarcieux (1753), Smeaton, (1752–1759), Papecino d' Antoni (1759–1762), Bossert (1770), Nordwall (1790–1800). Much of this study was directed towards the analysis of the types of water wheel then common, but Segner (1750) had brought out a simple

type of reaction wheel which attracted Euler's attention and an attempt was made to analyze the mechanical problems involved. Euler also developed the concept of Segner and produced a crude but explicit form of turbine wheel. The general aspect of the apparatus is shown in Fig. 137.[304]

"It consisted of two parts, placed one above the other. The upper was immovable and formed a cylindrical and annular reservoir, with small tubes fixed to the bottom, rectilinear, but inclined at an angle determined by calculation, and delivering the water

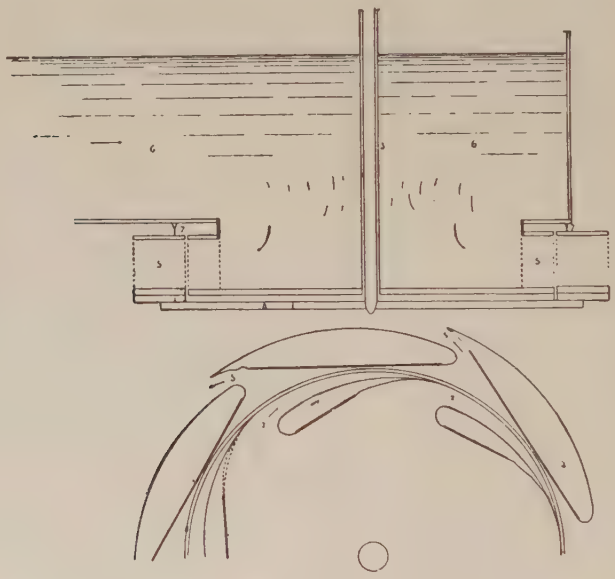


FIG. 138.—Burdin's reaction turbine, 1822.

upon the lower part. The latter, moveable around its axis, presented at the top an annular trough, from the bottom of which projected 20 tubes, diverging in their descent, the ends of which, bent horizontally, delivered the water in the air. All of these pipes were covered, as far as the bending by a smooth sheet-iron surface, designed to lessen the resistance of the air."[305]

Some commercial use was made of the machine, but it was not itself of any large significance.

The principle of these reaction wheels of Segner and the Euler, Leonard and Albert, was made the subject of systematic instruc-

[304] D'AUBUISSON, Fig. 68 *bis*.

[305] D'AUBUISSON, p. 444.

tion by Burdin in the technical school at St. Etienne in the early part of the nineteenth century. Burdin endeavored to improve the efficiency of these wheels and worked on several designs, some closely following the scheme of the Euler, one at least significantly different. The more original of his wheels was developed as early as 1822, and is described in the memoir presented to the Academy of Sciences in 1827. The principal features of this wheel are shown in Fig. 138.[306] The wheel is completely submerged. The water is guided into the vanes of the wheel by a stationary core divided into compartments by guide vanes. The general concept is thus identical with the arrangement of the wheel perfected by Fourneyron and, as Fourneyron was closely associated with Burdin as student and collaborator, it seems likely that these concepts of the teacher were not without influence on the pupil. Burdin's concept, however, contained defects which were fatal: the relatively flat surfaces of the mobile vanes would fail to secure the full effects of impulse and reaction essential to the significant operation of the wheel. The scheme was so definitely inadequate that Burdin returned to the principles of Segner and Euler in his later work and built wheels on those plans.

The importance of Burdin's work lay chiefly in its influence upon Benoit Fourneyron who was a student at St. Etienne in the years 1817–1819. Fourneyron became interested in the problems of the reaction wheel and continued his study of the practical problem in connection with his work at the iron forges of the region. Active work on the turbine began in 1823 and by 1827 Fourneyron had produced a small turbine capable of developing about 6 horsepower. It was in this year that the Society for the Encouragement of National Industry awarded to Burdin a portion of its prize for "the best application, on a great scale, of hydraulic turbines, or wheels with curved floats, of Belidor, to mills and manufactories." They also announced the extension of the competition until 1832 in hopes that the problem of the turbine might be more completely solved. Fourneyron moved to Besancon and devoted a large part of his time to work on the turbine with the financial assistance of F. Caron, a forge master of Fraisans (Doubs), who ordered at once a 10-horsepower wheel for his blowing engine and shortly after a 50-horsepower wheel for the forge hammers.[307] In 1832, the 50-horsepower wheel was completed; a

[306] Crozet-Fourneyron, "*L'invention de la turbine*," p. 23, Fig. 12.
[307] *B. G. T. I.*, Vol. V, pp. 83–84.

patent was taken out, and a memoir was submitted to Society for Encouragement of National Industry to place the new invention in competition for the prize of 6,000 francs. There were three other competitors, but the prize was awarded to Fourneyron. Two

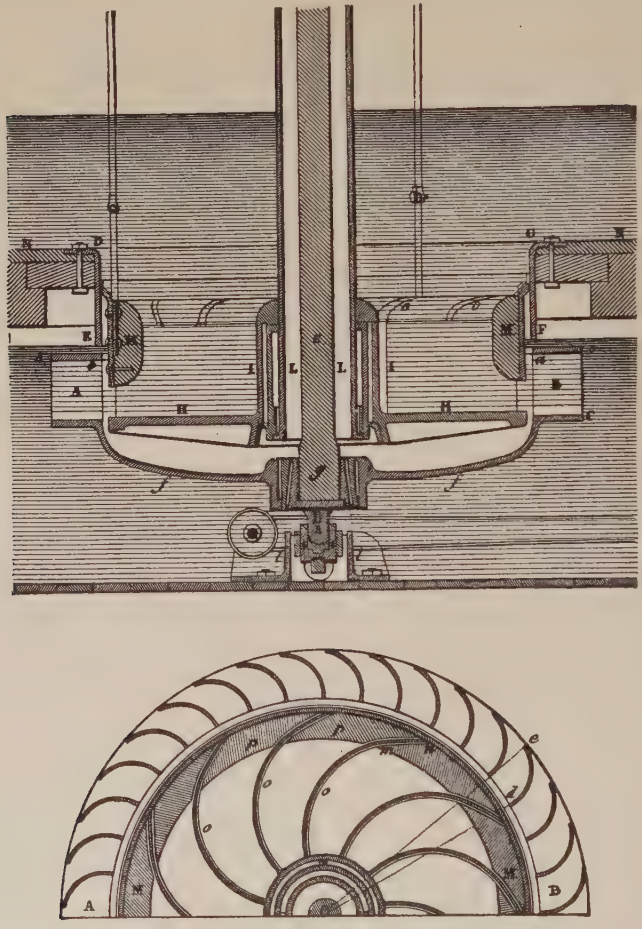


Fig. 139.—50 h.p. Fourneyron turbine, 1832.

elevations of the wheel at Fraisans are shown in Fig. 139.[308] There is a stationary cylinder *DEFG* with a bottom *HH*, containing guide vanes *oo*, and equipped with circular gates *mm* by means of which the water may be shut off. The rotating element surrounds

[308] D'Aubuisson, Fig. 102.

this cylinder and is connected with the driving shaft by the frame *ff*. The rotating part *AB* consists of two annular plates of iron containing 30 curved vanes. The water enters the fixed cylinder and is directed by the guide vanes against the vanes of the turbine, which is driven by a combined effect of impulse and reaction. At Fraisans, the wheel worked under a head of 4.59 feet; its diameters were 9.5 feet outside, 7.87 feet inside. A wheel set up at St. Blaise, in the Black Forest, worked under a head of 354 feet and though only 1.8 feet in diameter developed 40 horsepower. No hydraulic motor had hitherto been capable of developing so much power under such diverse conditions.

The principle of the turbine was, however, susceptible of much variety in design and a considerable number of important patents were taken out in the years 1832–1855. The direction of the flow may be radial, at right angles to the axis of revolution; axial, parallel to the axis of revolution; or, radial and axial flow may be combined. Radial flows may be outward or inward: axial flows may be downward or upward. There are also two distinct types which are not very happily designated as reaction and impulse turbines; for neither type is exclusively actuated by reaction or impulses. The reaction turbines are chiefly distinguished by the fact that they must be completely filled with water; the outlet may be submerged or above the surface of the tail race. Impulse turbines on the contrary, are always partially filled with air and their decisive success turned upon the introduction by Girard of a device for ventilating the vanes. The practical value of this type lies in its adaptability to streams of variable flow and to the conditions created by very high falls with small volumes of water. In this last case, the best dimensions of a reaction turbine become inconveniently small, whereas the impulse turbine can be made of larger diameter.

A representative form of the Girard impulse turbine is shown in Figs. 140, 141, and 142.[309] The guide vanes, and rotating members are shown in the general assembly at *W* and W^2; and in detail in Fig. 141. The detail of the guide vanes, rotating vanes, and the movement of the water through them is shown in Fig. 142. The air spaces at the inner bend will be noted, and it will also be noted that the water does not completely occupy the intervals between the vanes at the point of outflow. The wheel discharges into the air a little above the level of the tail race.

[309] Bodmer, p. 45, Fig. 30; p. 45, Fig. 31*a*; p. 253, Fig. 121.

The fact that most of these important variant types were the work of Fourneyron's late contemporaries has doubtless distracted

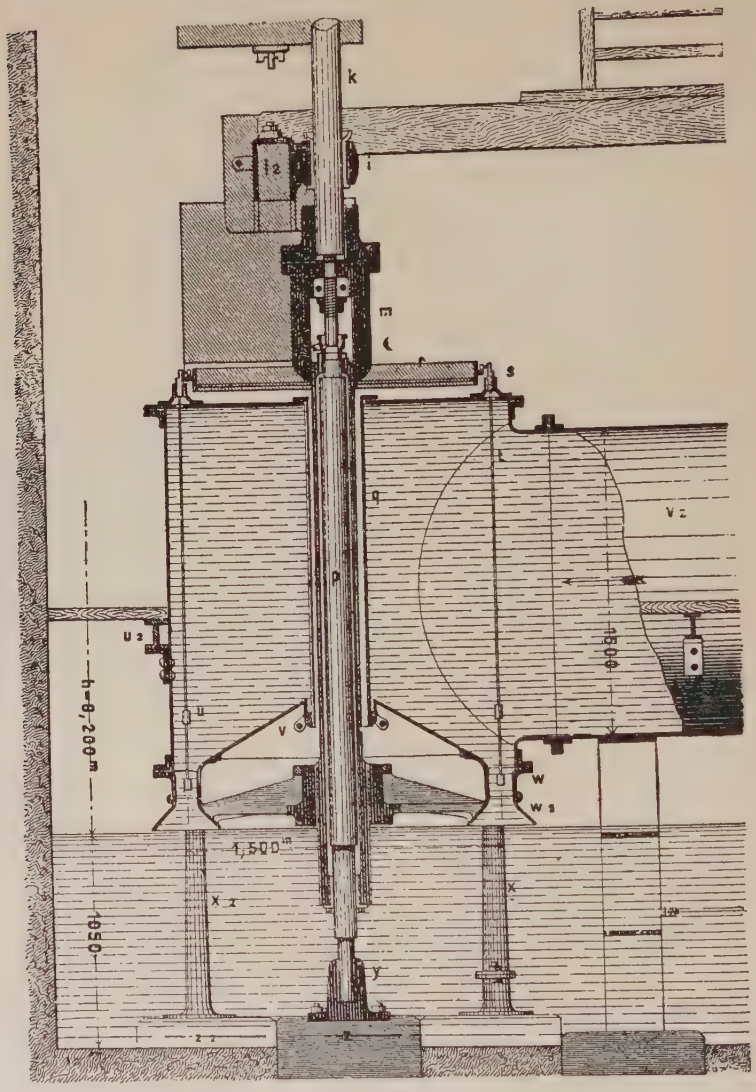


Fig. 140.—Girard turbine, 1855.

attention from his work. His wheels were all reaction turbines with radial flow outward. An important modification was

brought out by Thompson (1851) and Francis (1855), with radial flow inward. This became the dominant American type. In 1841, Jonval brought out a reaction turbine with axial flow, both downward and upward. Reaction turbines with combinations of radial and axial flow were also brought out. Among the impulse

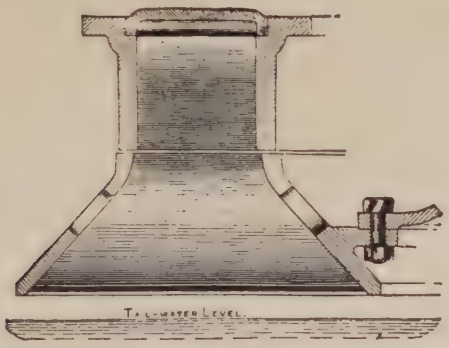


FIG. 141.—Girard turbine, detail.

turbines, radial-flow wheels have been of minor importance, though some practical forms were brought out, notably by Zuppinger. The most important type is the axial-flow Girard turbine described above, both downward and upward flows are designed. It was

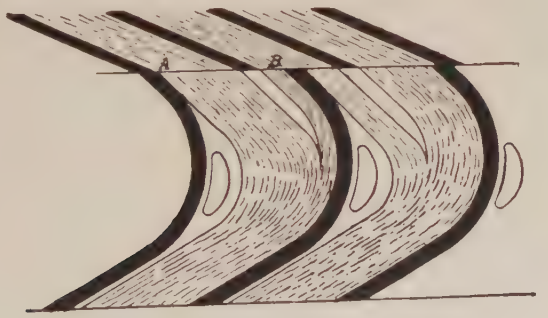


FIG. 142.—Girard turbine, detail.

unfortunate for his fame that Fourneyron's radial-flow reaction turbine was less well adapted to the small erratic streams of Europe than the Girard impulse turbines, and that in America the development of the reaction turbine came to be dominated by the inward-flow types of Thompson and Francis.

II

The general principle of the turbine can be utilized with steam as the pressure medium, and Fourneyron was occupied for many years with the technical problems of this adaptation, but without

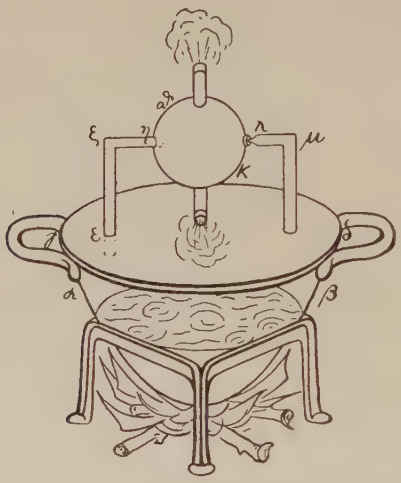


FIG. 143.—Hero's reaction steam turbine.

success. It is generally held that the actual development of the steam turbine was based on experimental work with principles embodied in Hero of Alexandria's reaction sphere, and Branca's

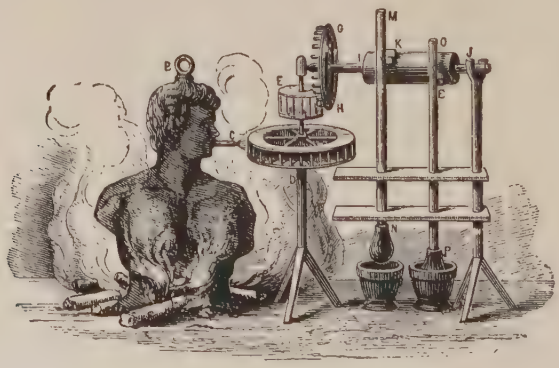


FIG. 144.—Branca's impulse turbine, 1629.

turbine. But the most casual study of these primitive machines will suffice to emphasize the difficulty of applying these principles in a mechanically sufficient form upon a commercially significant

scale. These early machines are shown in Figs. 143 and 144.[310] The transition would seem to be influenced in some measure by the development of the hydraulic turbine, but there is little detail available on the early work of de Laval and Parsons.

Gustav de Laval was moved to make a study of the turbine by the difficulty of procuring a motor capable of producing the high speeds required by his centrifugal cream separator. After studies of both the earlier types he evolved, in 1882, a simple and efficient impulse turbine which was based upon the principle of Branca's machine. It involved, however, refinements in mechanical concepts which make it, in fact, an entirely distinct machine. The essential features of the de Laval turbine are shown by the diagram in Fig. 145.[311] A wheel fitted at the edge with curved vanes is set in motion by the combined impulses and reactions produced by the flow of steam directed against the vanes by one or more nozzles. The term "impulse" wheel is infelicitous because the effective forces include considerable reactions. The distinctive feature really lies in the fact that the channels between the vanes are equal in breadth throughout their length so that no expansion of steam takes place while it is traversing these channels and there is thus no change in steam pressure. This type is thus accurately described by the German term "equal pressure" turbine. Expansion of steam takes place in the nozzles which are given an appropriate flare between the throat and the outlet. The perception of the importance of this expansion and the determination of the correct design of the nozzles were among the more notable achievements of de Laval.

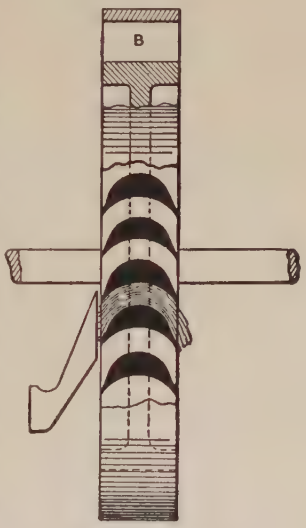


FIG. 145.—Impulse turbine.

The complete machine involves mechanical features of a high order, not readily appreciated by the layman. The rotor is, of course, enclosed in a casing, which must be closely adjusted to

[310] SCHMIDT, "*Heronis opera*," Vol. I, p. 230, Fig. 121; THURSTON, "Steam Engine," p. 17.

[311] MOYER, pp. 62–63, Fig. 36.

prevent leaking of steam. The accuracy of workmanship required would have been unattainable prior to 1840. Owing to the difficulty of making the center of gravity coincide exactly with the center of revolution, some allowance must be made for play on the bearings and specially designed bearings were essential. The speeds attained required grades of steel which could not have been produced with certainty much before the latter part of the nineteenth century. Reducing gears were required of better workmanship than any previously produced. The realization of a principle conceived in the seventeenth century thus involved most of the primary technological achievements of the entire intervening period.

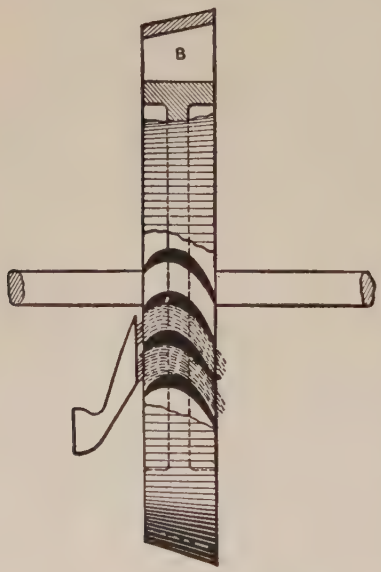


Fig. 146.—Reaction turbine.

Within two years of the patenting of the de Laval turbine, Charles A. Parsons took out his patent for a "reaction" turbine whose general industrial significance was somewhat more immediate, though it was not intrinsically a more meritorious achievement. The essential principle of this turbine is shown in Fig. 146.[312] The shapes of the blades differ from those used in the impulse turbine, and provision is made for expansion of steam during its passage among the blades and, consequently, a drop in pressure occurs. This type is thus more accurately characterized as an "unequal pressure" turbine. The schematic diagram, however, is not an adequate representation of the primary features of the Parsons turbine. These machines contained at the outset many rings of moving blades and steam was admitted simultaneously to all the blades in each ring by stationary guide blades fixed in the casing. The detail of this arrangement is shown in Fig. 147,[313] but the general aspect of the machine will

[312] Moyer, p. 63, Fig. 37.

[313] Stoney, G., "Steam Turbines," *J. R. S. A.*, Vol. 57, p. 954, Fig. 1.

be more readily seen in the sectional drawing reproduced in Fig. 148.[314]

"The steam enters at *A* on the lower half of the cylinder, thus leaving the upper half quite clear of steam pipes and all obstructions and facilitating dismantling. It then passes successively through the different rows of fixed and moving blades, . . . and leaves the cylinder through the exhaust pipe *B*. In order to give increased passageway to the steam as it expands, the shaft is made with three steps of different diameter, the height of the blades being also increased. The steam, in addition to its rotational

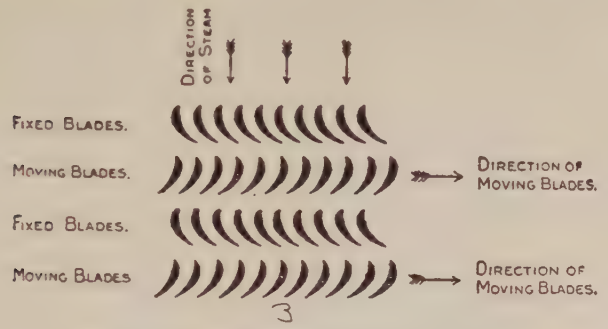


Fig. 147.—Elements of the Parsons turbine.

force, exerts a pressure endways along the shaft on the surface of the blades and the shoulders of the shaft. This is balanced by the dummy pistons, c', c'', c''', as shown in the section. They are made of diameter corresponding to the different parts of the turbine they balance, and are supplied with corresponding steam pressure through the pipes P', P''. The shaft thus runs in complete balance endways, and can be moved backward and forward with a light lever, even when the turbine is running under a full load. In order to prevent steam leakage, grooves are turned in these pistons, into which project, without, however touching the moving parts, suitably shaped strips of brass caulked into grooves in the cylinder. The whole forms a labyrinthine passage offering great resistance to the escape of the steam, most of which is carried round and round by the skin friction of the dummy pistons, producing a most effective screen against leakage. The two glands *D*, where the shaft leaves the turbine casing, are constructed in precisely the same manner."[315]

[314] Stoney, G., "Steam Turbines," *J. R. S. A.*, Vol. 57, p. 956, Fig. 2.

[315] Stoney, G., "Steam Turbines," *J. R. S. A.*, Vol. 57, p. 955.

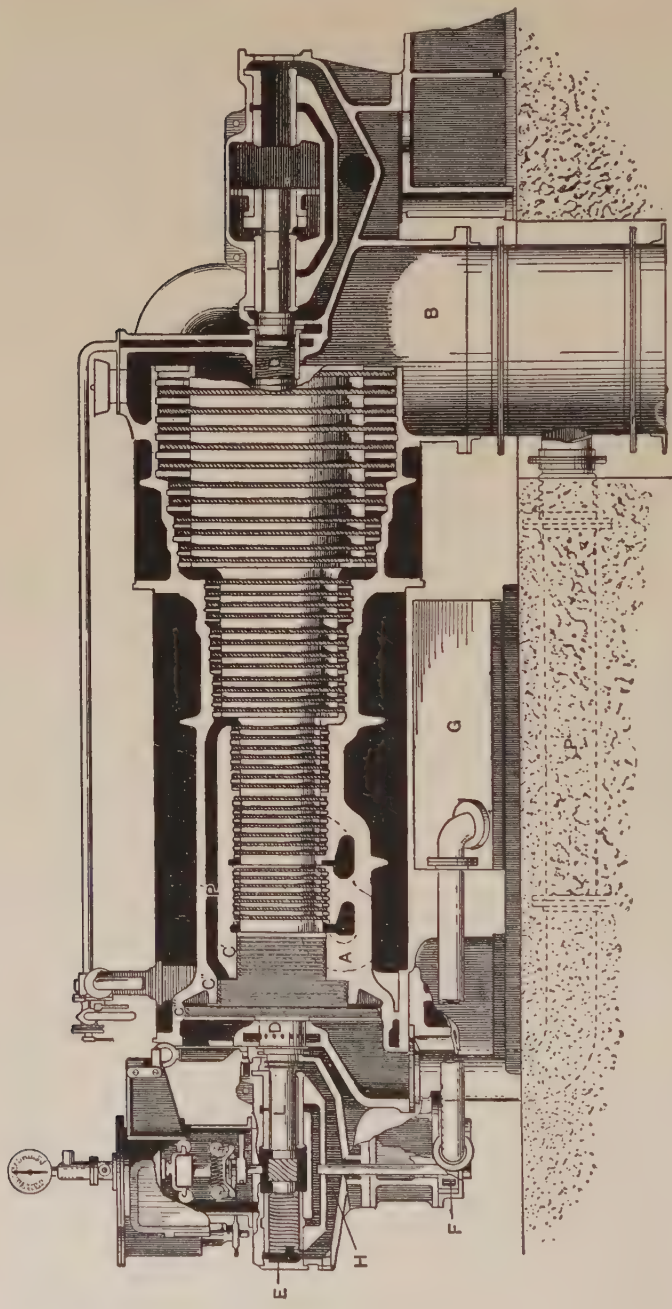


FIG. 148.—Developed Parson's turbine.

This design was brought out in 1894 and first installed on a considerable scale in London at the Manchester Square Station of the Metropolitan Electric Supply Company. Since that time the general style of the Parsons turbine has not been significantly changed, though there are now many variants of this type.

At the outset, the impulse and reaction turbines, represented respectively by the de Laval and Parsons patents, commonly displayed a number of practical differences of genuine importance in the early applications of this type of engine to industrial use. The de Laval turbines were built for smaller units ranging from 5 up to several hundred horsepower. They revolved at very high speeds: the speeds for the primary shaft ranging from 10,000 to 30,000 revolutions per minute. These speeds were reduced by specially designed reduction gears. Although some of the early Parsons turbines were built as small as 10 horsepower, the large sizes predominated. The shaft speeds were lower; no more than 18,000 revolutions per minute in the early days, and later, in very large units speeds, as low as 750 revolutions per minute were attained. These practical differences have tended to disappear, notably in the Curtis turbines, and in the multiphase de Laval turbines which were ultimately developed.

The steam turbines as a class exhibit some striking differences in comparison with reciprocating engines. When the first large dynamos were built, Edison found no little difficulty in finding an engineering firm willing to undertake the construction of a reciprocating engine capable of 350 revolutions per minute. Dynamos were commonly run at speeds of 1,000 to 1,500 revolutions per minute, so that the reciprocating engine required gearing or transmitting mechanism to secure the high shaft speeds needed by the dynamo. The limitations of the turbine were of an opposite character and as lower speeds became possible with an increase in size, the turbines were soon placed in a preferred position for the generation of electrical energy.

These high speeds of the turbine are achieved with a minimum of vibration, as the motion of the turbine is a pure rotary motion. In some locations this relative absence of vibration is of substantial economic importance.

There are practical limits to the sizes of the different types of engines, and just as Watt's engine was capable of developments on a larger scale than Newcomen's atmospheric engine, so the turbine can be built on a larger scale than the modern reciprocating

engine. The limits of the reciprocating engine were not significant when the power plant was designed to meet the needs of a single industrial establishment, but the development of central power stations in the electrical industries created new demands for power which the reciprocating engine could not meet effectively. Insull says, that between 1890 and 1900 the triple-expansion marine engine was worked up to a maximum capacity of 5,000 to 6,000 kilowatts (about 6,500 to 7,800 horsepower). But this seems to be the limit of the development of the reciprocating engine.[316] The first marine turbine installation (1894–1897) consisted of three turbines yielding in all 2,000 horsepower, and in 1906 the plans for the *Lusitania* and *Mauretania* were completed calling for four turbine units in each vessel of about 17,500 horsepower each. Two years later, Moyer declared that it was generally admitted that there would be no more installations of large reciprocating engines for the production of electricity, and in 1917 the same writer declared that 70,000-kilowatt (91,000-horsepower) steam turbine units were possible. In 1921, there were in the United States a considerable number of steam-turbine units of 30,000 kilowatts (39,000 horsepower), and in the Super-Power Project the plans for new steam base plants contemplated standard single-cylinder units of 30,000 kilowatts, with some multiple-cylinder units of 60,000 kilowatts. It is thus fairly evident that the practical limits of this new engine are not yet known, and if 8,000 horsepower is indeed the limit of the reciprocating engine, the possibilities opened up by the turbine are of obvious importance.

Partly by reason of increased efficiency in the utilization of heat energy, partly as result of the great increase in size possible, the steam turbine achieves economies in the use of coal that are still incompletely exploited. With Smeaton's improvements, the Newcomen engine consumed 15.87 pounds of Newcastle coal per hour for each effective horsepower; Smeaton's tables for computed or indicated horsepowers, however, assume coal consumption as low as 11.76 pounds per horsepower per hour. The variations in the heating power of the different grades of coal amounted to as much as 20 per cent, so that attention must be given to the specification of coal.[317] As the Newcomen engine was considerably

[316] INSULL, SAMUEL, "Central Station Electric Service," p. 349, Chicago, 1915.

[317] FAREY, "Steam Engine," pp. 173, 183, 368; JENKIN, A. H., "The Cornish Miner," p. 101.

improved by Smeaton, it is perhaps true as alleged by some that it consumed as much as 20 pounds of coal per horsepower per hour when it was first brought out. About 1780, Watt's engine consumed per horsepower per hour, with expansion 6.26 pounds of Newcastle coal, without expansion 8.4 pounds.[318] The reciprocating engine underwent substantial improvements and records of tests indicate considerable reductions of coal consumption; some figures being given as low as 1.9 pounds per horsepower per hour.[319] But in these trials, computations are based commonly on the indicated horsepower rather than the effective horsepower and conditions of firing for a test are substantially better than in general practice, so that such figures are not wholly comparable with the kinds of figures available for a comparison of the relative efficiency of reciprocating engines and turbines in the present century. The recent figures are records from the actual operation of the large central power stations over long periods of time. The Edison station at Chicago used in 1900, 6.90 pounds of coal per kilowatt hour (5.17 pounds per horsepower hour). In 1913, with turbines, coal consumption was 2.87 pounds per kilowatt hour. In 1924, turbines at the Duquesne Light Company's Colfax station at Pittsburgh consumed 1.29 pounds per kilowatt hour or 0.96 pound per horsepower hour.[320] The development of the large turbines has thus resulted in fuel economies roughly proportionate to the economies realized by Watt's engine in comparison with the Newcomen engine. The steam turbines must thus be regarded as inventions of absolutely first-class importance. They have already transformed the production of electric power, and it is noteworthy that these inventions gain much of their significance from the electrical inventions contemporary with them.

Apart from the electrical industries the most important field of development for the turbine has been in marine use. As early as 1894, a syndicate was formed to exploit the Parsons turbine as a marine engine. There were two serious difficulties to be overcome: the reduction of the shaft speed of the turbine rotor to rates of effective screw-propeller operation; the provision of a reversing mechanism. The problem of speed was solved by careful study of the proportions of the turbine rotor. For reversing, a special

[318] FAREY, "Steam Engine," pp. 367–368.

[319] THURSTON, "Engine and Boiler Trials," p. 385.

[320] INSULL, SAMUEL, "Central Station Electric Service," p. 469; QUIGLEY, H., "Electrical Power and National Progress," p. 36.

turbine is requisite, if the power of the turbine is utilized directly. The experimental work on the "Turbina" between the years 1894 and 1897 established all the primary features of the marine turbine. Two destroyers, the *Viper* and the *Cobra* were built for the British Admiralty between 1897 and 1902; and in the latter year the first commercial order was executed for a merchant vessel, the *King Edward*, designed for the channel service. The Admiralty proceeded rapidly with the turbine, first to third-class cruisers and finally to the famous *Dreadnought*. The future of the turbine at sea was decisively indicated by 1906 when the Admiralty adopted it for all fighting ships and the Cunard Company gave its order for the *Lusitania* and *Mauretania*. The accomplishments of these liners are too well-known to require comment, and although the significance of the *Dreadnought* is commonly associated with its armament, its speed was of course a vital part of the new conception of the battleship.

The marine turbine in this form was economical only at high speeds, and there was some disadvantage in not having full power available for reversing. For naval use, important results have been achieved by generating electricity with the turbines to operate motors on the propeller shafts. Such a system admits of more flexibility of operation than in the case of turbines connected directly with the driving shafts. In the merchant service, turbines are combined at times with reciprocating engines. The newer motor has thus made a distinctive place for itself without supplanting the reciprocating engine in those uses best served by low speeds of the driving shaft.

III

Both hydraulic and steam turbines find their most conspicuous utilities, however, in large electric generating stations. The great water powers of the world could not be utilized on a grand scale as long as the transmission of power was dependent upon mechanical connections with the driving shaft of the prime mover. No industry required more than a small proportion of the power available. Except for the production of electricity there was no industrial demand for the large steam-turbine units that could be constructed. The new phases in the centralized generation of power are thus jointly due to the new prime movers and to the development of the electrical industry as a medium for the transmission and distribution of power.

It is neither necessary nor possible to enter into the full history of the discoveries and inventions that have made the modern electrical industry, but it is important to note the chronology of some of the strategic inventions. The early history of electricity centers around various types of accumulators, dry cells, and wet batteries. The telegraph and telephone were based upon such sources of electrical energy and their perfection brings to a close the first distinctive period in the application of electricity. The next period of application is marked by the invention of the motor and dynamo, and the applications of electricity to lighting, traction, and industry. The basic achievements are the dynamo-motor and the lighting system with a central power plant.

The primary principles of the dynamo were discovered by Faraday in 1831. H. Pixii soon worked out many details for the application of this discovery first (1831) to the production of an alternating current, later (1832) adding a commutator by which a direct current could be drawn off the brushes of the machine. In 1845, Wheatstone substituted electromagnets for the natural magnets that had been used up to that time, and thereafter possibilities of a substantial increase in the compass of dynamos were opened up. Many inventors worked at the dynamo and the primary variations of winding were worked out before 1870, but these machines produced a current that was so variable in intensity that they were of very restricted commercial use. A few arc-lighting systems were run by dynamos and some electroplating was done; Wheatstone had used small dynamos in some of his telegraphic installations, but most electric current was still furnished by batteries. The decisive step forward was taken in 1865 and 1870. Pacinotti (1865) improved the methods of winding and secured a steady current, but his work seems to have gained no publicity and the same principles were embodied in the famous ring armature of Z. Gramme (1870). In this case, as in so many others, the strategically important invention was a critical revision of an existing machine.[321] At the Vienna exhibition in 1873 it was accidentally discovered that Gramme's dynamo was, in fact, a reversible engine and could be used as a motor.

After this achievement the development of the electrical industries proceeded rapidly, and before 1880 the primary accomplish-

[321] These early dynamos are described and illustrated in HOWELL and SCHROEDER, "History of the Incandescent Lamp," pp. 15–25; see also, FLEMING, "Fifty Years of Electricity," pp. 43–49, 109–147.

ments in lighting, power production, and traction were practically realized.

The development of the incandescent light was in many ways the outstanding achievement as it involved the central electric station. The decisive work in this field was done by Edison, and though the actual innovations may seem small, they were in fact of commanding importance and a striking indication of that inventor's unusual fertility of conception and critical power. The incandescent light had been demonstrated as early as 1820 by De la Rue, using a coil of platinum wire and a piece of glass tubing. Thereafter, the incandescent lamp engaged the attention of a long series of inventors in Europe and in the United States. Platinum, iridium, carbon rods, carbon strips, and graphite were tried; sometimes, the lamp was covered with a globe, with or without a vacuum. In the earlier years the vacua that could be obtained were poor, but the invention of Sprengel's mercury pump opened up new possibilities, and Swan one of the leading experimenters repeated his trials of carbon elements in the high vacua then attainable in completely sealed glass globes (1878). Swan's results were encouraging, but his lamp was not a solution of the problem.

Accordingly, when Edison addressed himself to the problem in the fall of 1877, many were disposed to believe that nothing practical could be made of these enticing laboratory demonstrations. The lamps were expensive to make and to operate, and so short lived that there seemed to be no prospect of a general application of this principle. All the hopeful leads seemed to be exhausted. Experimental study seemed to indicate that carbon in all its forms was a failure, so the first constructive work was based on platinum, and in October, 1878, the first lamp patent was applied for covering a platinum lamp protected by a thermostat to short circuit the burner when the current was too high. Various other lamps were made, without significant success and, consequently, Edison's attention was turned for the moment to the general design of a lighting circuit. It was, in fact, as much of a problem as the light itself, for all arc-lighting systems were then wired in series so that all the lamps must needs be operated continuously, as the failure or shutting off of any one lamp broke the whole circuit. Edison conceived the parallel circuit and worked out all the primary details of the wiring; the mains, the house circuits, and the connections with the dynamos.

This work, which was highly original throughout, redefined the problem of the lamp; for no adequate illumination could be secured unless the resistance of the lamp were increased far above any limits previously tried. A platinum high-resistance lamp was tried, but even after several trials the platinum lamp consumed a disproportionate amount of current and was short lived (April, 1879).

In the fall, Edison turned again to carbon. A near contemporary account of the genesis of the carbon filament has been cited in an earlier chapter. It seems to be based upon an interview with the inventor, but it is unfortunate that we have no more direct account. The innovation consisted in the proposal to use a very fine filament of carbon. All previous work with carbon had been based on relatively large rods or ribbons of carbonized paper. The new concept was, in part, a result of the reasoning based upon the requirements of the proposed lighting circuit; but it was, of course, a curious situation, as it involved the repetition of experiments that seemed to have led only to failure.

The technical problem of preparing filaments presented many difficulties. These early experiments were based on treating sections of sewing cotton in a specially constructed furnace. When several had been produced, they were fixed in glass globes which were exhausted with the mercury pump. Before sealing the globe, however, Edison took one more new step. He had concluded from previous experiments that gasses were occluded in the carbon itself, which would blacken the globe and reduce the efficiency of the lamp if allowed to remain. The filament was therefore heated slightly by passing a current through it, and it then required nearly 8 hours to exhaust the gasses thrown off.[322]

The first carbon filament was demonstrated in the laboratory at Menlo Park, Oct. 21, 1879. The lamp burned steadily for nearly 2 days. The details of the preparation of the filament were then made the subject of intensive study and filaments of carbonized bristol board were finally prepared that gave several hundred hours of life. Public announcement of the invention was made in the New York *Herald* of Dec. 21, 1879, and a demonstration was arranged at Menlo Park. Sixty lamps were strung on poles in the laboratory grounds and a few lights were installed in several

[322] There are discrepancies between the accounts of the work of Edison and Swan which it is not easy to reconcile. FLEMING, pp. 157–158; HOWELL and SCHROEDER, pp. 56–58.

houses. The patent was applied for on Nov. 4, 1879, and granted Jan. 27, 1880.

The first commercial installation was on the steamship *Columbia*, of the Oregon Railway and Navigation Company. The plant was started May 2, 1880 with 115 lamps, remaining in operation for 15 years without any substantial change. On land, the first commercial installation (1881) was in the lithographing shop of Hinds, Ketchum and Company, 229 Pearl Street, New York. Other customers were found in New York, and installations were made elsewhere. The first public-service station was put into operation at Appleton, Wisconsin, in 1881, and in 1882 central stations were established at Pearl Street in New York; Holborn Viaduct, London; Sudbury, Pennsylvania, and Milan, Italy. In these central power stations, Edison realized the concept that had dominated all his work with the light, and his essential achievement was this combination of electrical devices in a comprehensive system for the production and distribution of electricity. The realization of this bold concept involved an immense amount of inventive and critical effort, as every phase of the work created entirely new problems. The dynamos embodied many novel features; the technique of wiring had to be developed; meters were required; fixtures were to be designed; last, but by no means least, the steam engine required improvements to increase the regularity of its operation.

" . . . On many occasions it was necessary for Mr. Edison to take off his coat and practically instruct the workmen in the laying of street mains or the running of dynamos in parallel at the supply station. At first it was considered quite a feat if a dynamo could be kept going for a day or so without some failure necessitating a stop for repairs."[323]

As soon as the primary technical features of the central station were solved, economic problems arose which furnished powerful motives for great extensions in the utilization of electricity. The building and equipment of the station and its distributive system required large outlays of capital, whereas the demand for light was confined to a relatively small portion of the total running time; the effective demand was concentrated in 6 or 7 hours of the 24 and for much of this period only a portion of the possible energy was needed so that in residential districts only 10 or 12 per cent of the possible output was actually required. Economical opera-

[323] FLEMING, p. 225.

tion of such a station can best be achieved with the fullest possible utilization of the productive capacity of the plant. The electrical station has thus a powerful incentive to encourage industrial uses of electricity, and there are evident advantages in the complete centralization of all power requirements.

The movement towards centralization has been proceeding simultaneously from several directions; electricity has steadily worked its way into a larger range of industrial and domestic uses; improvements in the technique of transmission have constantly increased the radius of effective distribution or transport of electrical energy; improvements in the construction of prime movers have steadily created wider margins of advantage of central over individual power plants; and the possibility of distributing electricity generated by water powers in remote or inconvenient locations has altered profoundly the comparative advantages of extensive regions. Mineral fuels have become less important, and the possible use of water power has been so enormously extended qualitatively and quantitatively that many regions can now look forward to an industrial development that would have been utterly inconceivable in 1870.

Centralization of electrical production on this scale has been made possible by the development of long-distance transmission of alternating currents at high voltages. Because such currents are dangerous, Edison had presumed that general distribution must needs be restricted to low-voltage direct currents. But resistance is serious under these circumstances. Important pioneer work on long-distance transmission of direct currents was done by Marcel Deprez early in the decade 1880–1890. After 1885, notable work was done on the technical problems of the alternating current; its production, transmission, and transformation into low-voltage direct current. By 1891, the elements of the new technique were sufficiently established to lead to its adoption by the hydroelectric enterprise established at Niagara Falls. Power House number 1 was begun in 1891; this unit contained 10 turbines of 5,000 horsepower each, operating a two-phase alternating-current generator. This portion of the plant was brought into operation in 1897–1898, marking a new stage in the history of the production of power in this country, and roughly contemporaneous with similar developments in Europe.

Early in the present century, we find the beginnings of a comprehensive centralization of power production for large areas,

with interconnected power units. The most notable pioneer districts are the Chicago territory dominated by the Commonwealth Edison Company; the Northeast Coast Industrial Area in England, and the Elberfeld district in Germany. Latterly, large projects have been suggested in this country and in France, without any final public action, but large areas in this country and in Europe are now served by interconnected stations. In Great Britain, a comprehensive policy has been laid down in the Electricity Supply Act (1919) which was amended in 1922. Under these statutes the coordination of the production of electricity is proceeding steadily though not rapidly. Similar developments are, in fact, going forward in all the other countries, despite the absence of any comprehensive declaration of state policy. Ultimately, important economies will be realized in the use of mineral fuels; much waste steam will be conserved, and resources of water power will be fully utilized even when the flow of streams is highly irregular. The full economic consequences of such changes cannot now be foreseen, but it is perfectly clear that the fuller utilization of water powers and of the low-grade coals will profoundly affect the development of regions that have been handicapped in the past by the lack of adequate quantities of high-grade coal.

IV

The concept of an internal combustion engine was evolved in connection with very early studies of the use of a piston as a means of utilizing heat and pressure. Huygens (1680), and Papin (1690) made some experiments that involved basic concepts, though nothing approaching a complete engine appears until the close of the eighteenth century. The English patent of Robert Street (1794) and the French patent of Lebon (1799) mark the beginning of a long series of efforts that did not yield significant practical results before 1860. The history of these inventions demonstrates admirably the complexity of the process of achievement, but it is not necessary to insist further upon its general features. The separate elements of the gas engine were evolved in this period of experimentation: the ignition systems, at first flame ignition and later electric-spark ignition; compression of the explosive mixture; water cooling of cylinder and pistons. Some machines were built for practical use, but none were placed on sale generally. In 1860, by combining known elements, Lenoir produced a

practical engine for power requirements not exceeding 3 horsepower, and despite a large consumption of gas his engine came into significant use in a wide variety of situations. The causes of its lack of economy were not at first understood, but discussions of the next 2 years led to notable formulations of the primary requisites of such engines by Schmidt (1861) and Alphonse Beau de Rochas (1862). Schmidt stressed the vital importance of compression of the explosive mixture. Beau de Rochas suggested that the various operations taking place in the cylinder be reduced to a cycle requiring, in all, four strokes of the piston: intake of the gas during the entire up stroke of the piston; compression, by means of the down stroke; ignition at the dead point and power producing expansion on the second up stroke; and expulsion of the burned gasses during the second down stroke.

This concept of the four-cycle engine was finally embodied in an effective form by Otto in 1876. This engine rapidly supplanted all its competitors and became the basis of all the modern gas engines irrespective of the original form of the fuel; the light petrol engines, and the heavy oil engines are both variants of the basic type though they involve many special details. Subsequent to this date, the engines using gas as fuel began to compete more effectively with other prime movers for general industrial use, as they were no longer restricted to a maximum of 3 horsepower. After the discovery in 1895 that blast-furnace gasses could be used in these engines, they came into extensive use in iron and steel works and began to be built in large units.

Daimler brought out in 1883 a high-speed gasoline engine for motor vehicles and small boats. Gas engines were then designed for 200 revolutions per minute, this new gasoline motor attained a speed of 800 revolutions, and this speed was soon increased. The manufacture of motor vehicles was begun under Daimler's direction in Germany and in 1889 arrangements to use the Daimler engine were made by Panhard and Levassor in France. The gasoline motor applied to vehicles in 1878 by Benz at Mannheim did not differ in any fundamental respect from the larger gas engines made by his firm, so that the achievements of Daimler were more significant for the future development of the distinctive types of gasoline motor. Although the basic features were taken over from the Otto four-cycle gas engine, the necessary modifications presented problems of great difficulty and the full potentialities of the new motor were achieved only after considerable effort.

The heavy-oil engines begin to assume characteristic form with the efforts of Priestman at Hull in 1885. The special problems presented were most adequately solved by Rudolf Diesel whose first engine was produced in 1895. It was at first presumed that these engines were destined generally to supplant coal-burning engines, but it has become evident latterly that coal is the more abundant fuel; and cheaper, except under special circumstances. The heavy-oil motor is thus a supplementary source of power that is likely to find its fields of use restricted by various special circumstances; notably in marine transport at low speed.

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